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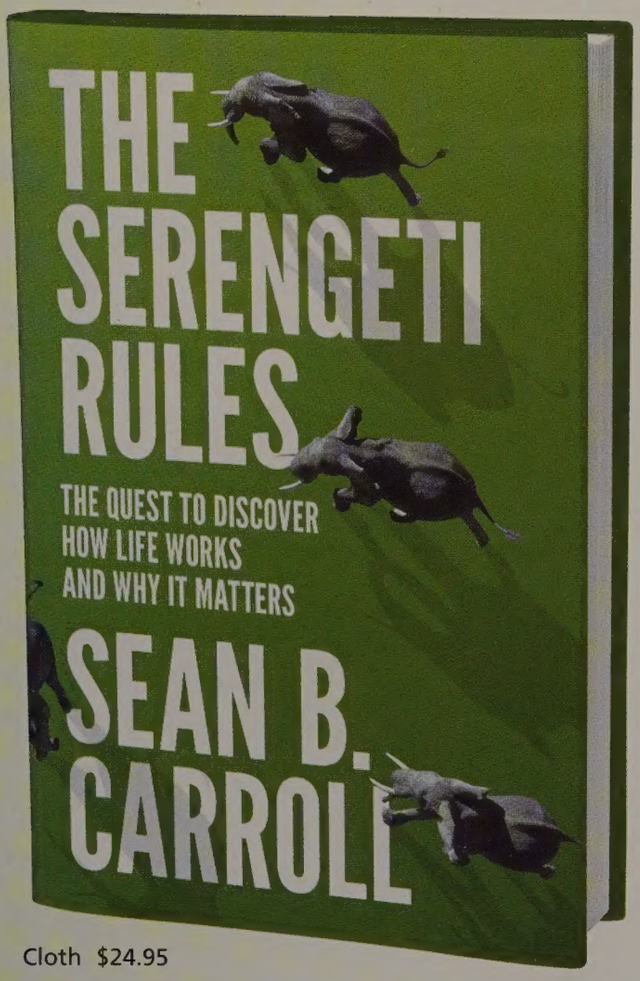

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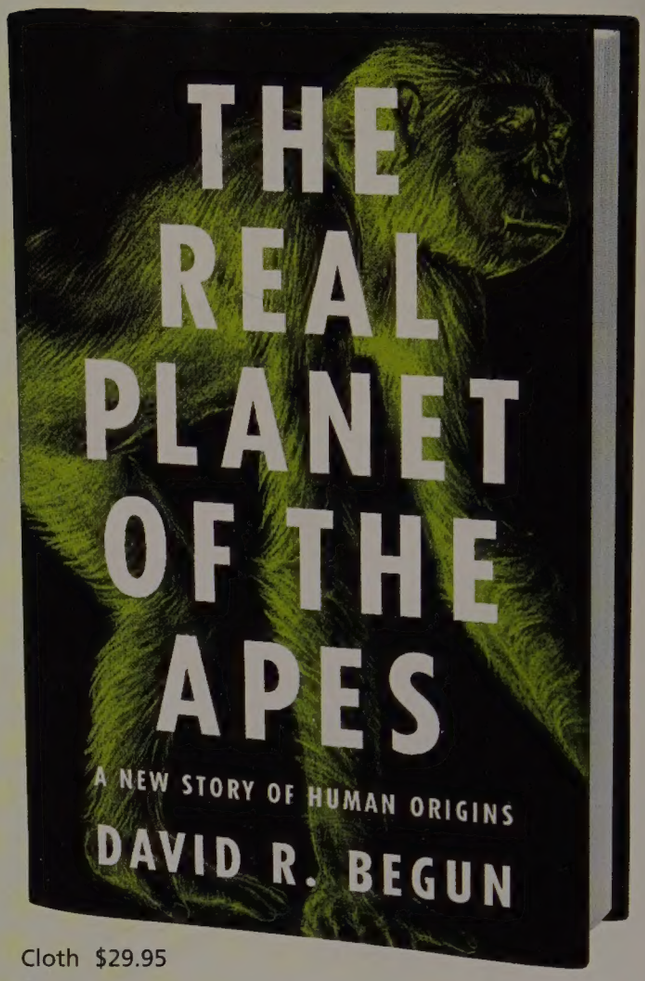

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NATURAL HISTORY

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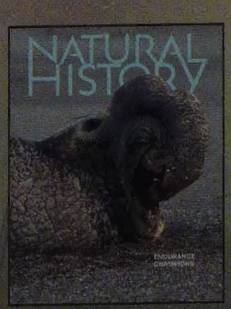

ON THE COVER:

*Northern elephant seals (*Mirounga angustirostris*) are able to hold their breath longer and dive deeper than all other pinnipeds and most whales. Adults are also able to fast for as long as three months and still remain active.*

Photograph by Jacob Harris

THE NATURAL MOMENT

Face-off

Photograph by Bence Máté

◄ *See preceding two pages*

Bence Máté was photographing hummingbirds at feeders in Costa Rica's Monteverde Cloud Forest Reserve when he heard several of the birds making an alarm call—a sign that a predator was nearby. Máté recognized the call from having heard it a few months previously, when some hummingbirds were alarmed by an owl butterfly (genus *Caligo*), which has a large spot on each wing resembling the eyes of the predatory bird.

This time, the cause of the hummingbirds' alarm was a green pit viper (*Bothriechis lateralis*), pictured on the previous page. The snake was sluggish in the 45°F weather, and appeared to pose little threat to the green-crowned brilliant hummingbird (*Heliodoxa jacula*), though vipers are known to prey on hummingbird chicks still in the nest. Máté watched as first one hummingbird, and then a group of five or six, flew around the snake, producing the alarm call. They harassed the snake for a minute or two and left, only to return five minutes later. The birds repeated this pattern for about an hour before flying away for good. These intervals gave Máté time to set up a flash behind the snake, allowing him to photograph both bird and snake clearly, using a 1/100 second shutter speed and a 300 mm lens.

Máté is known for the elaborate "hides" that he constructs to observe and photograph animals in their natural habitats without being seen himself. This picture, however, was more spontaneous. "Usually I'm working for two, three months for one image," he said. "This image took one hour of work. At the end of the day, it's about being in the right place at the right time."

The photo shown on this page was even easier to capture. Máté simply taped his business card to a branch near one of the hummingbird feeders at the Monteverde tourist center and waited for an obliging hummingbird to land on it.

Bence Máté is an award-winning Hungarian wildlife photographer. In 2000, at the age of fifteen, he won Young Wildlife Photographer of the Year in Hungary. At age twenty-five, he was the youngest person, and only Hungarian, to win Wildlife Photographer of the Year worldwide. Often referred to as "invisible," Máté has constructed twenty-five effective photography hides in Hungary, Costa Rica, and Brazil. He is also the co-author of *The Handbook of Bird Photography* (Rocky Nook, 2013) and a contributor to a television miniseries from 2012, "The Invisible Wildlife Photographer." See more at www.matebence.hu.

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World Population 0001-2050

Some inventions have altered population history.

Inventions that have had the most profound impact on human population growth, according to the forty-eight-year old population stabilization organization Population Connection, have been the drilling of oil wells in China (347 CE), the magnetic compass (China, 1040-44), the microscope (Netherlands, 1595), the flush toilet (England, 1775), and nitrogen-based fertilizer (Germany, 1909). You might make a case for the inclusion of other inventions, but Population Connection explains on its website (**http://www.populationconnection.org/article/top-five-inventions-that-changed-population-history**) why it picked these five. If you want to see the impact that these inventions and that of other world events have had on human population growth and distribution, go to **http://worldpopulationhistory.org/**. This page features an interactive map and an under-six-minute video that show growth from year one of the Common Era to the present and project growth to the year 2050. By the end of the century, human population is expected to reach ten billion. The FAQ section of **http://www.populationconnection.org** includes the question, "But isn't it true that the entire population of the world could fit inside Texas?" The response: "Yes, and you could fit twenty people in a phone booth, but how comfortable do you think they would be?"

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WORD EXCHANGE

Chances Are

Druin Burch's article "Probable Cause" [12/15-1/16] highlights the difference between *a priori* and *a posteriori* explanations of reality. *A priori* thinking, i.e. independent of experience, is acceptable for developing hypotheses but is an undependable way of reaching verifiable conclusions. When backed by a powerful individual or institution, *a priori* thought hobbles progress, as did the writings of Aristotle and Galen in biology and medicine for over a thousand years, or as did Soviet biologist and agronomist Trofim Denisovich Lysenko during the Stalin regime. The usual result is what Thomas Henry Huxley called "the great tragedy of Science, the slaying of a beautiful hypothesis by an ugly fact."

Sadly, *a priori* thought is not limited to science and thrives in political philosophy and religion. So we get such beliefs as "the compound eye proves that there is a compound-eye designer," or "the market is self-correcting," or "property is theft," or that a specific religious text can answer all moral, political, and scientific questions.

Good scientific education should emphasize that science is not a collection of facts, but a way to evaluate evidence for a coherent understanding of the natural world.

William B. Saxbe, Jr.
Williamstown, MA

Little House on the Prairie

I was delighted to read a description and explanation of my home ecosystem ["Steppe by Steppe," 12/15-1/16]. Other readers may wonder how we adapt to living in "hail alley." Serious gardeners build hardware cloth and chicken wire hail guards over their vegetable gardens and look for native perennial flowers because they have spikey shapes and narrow leaves that are less likely to be shredded by hail. The Denver Botanic Gardens and Colorado State University, through their Plant Select partnership, bring plants from local grasslands and the other steppes of the world into the regional nursery trade.

When I first came to the Great Plains in 1978, my landlady, who homesteaded in northwestern South Dakota with her husband in 1914, told me to keep a quilt in my back seat to cover my car in case of hail. Episodes barely last five minutes, however, and the hail is often too big to go out safely and spread a quilt. Wisely, our house has a gravel roof, allowing stones to repel hailstones.

Barbara A. Gorges
Cheyenne, WY

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Butterfly Effects

For species living at the cooler edge of their habitat range, a warming climate should help them thrive. Yet various animals' observed reactions to climate change have not been so predictable: some species expand more than expected while others languish. What explains this variability?

KEITH WARMINGTON

*The comma butterfly (*Polygonia c-album, left*) increased in abundance from 1976 to 2012, while the grizzled skipper (*Pyrgus malvae, right*) decreased.*

Ecologist Georgina Palmer of the University of York in the United Kingdom and a team of seven colleagues examined this issue by studying butterflies and moths in Great Britain. Although all are at their northern limits, these members of the order Lepidoptera have been responding quite differently to the same broad changes in climate.

The team obtained records of local temperature and rainfall, as well as abundance and distribution of 155 moth and butterfly species, for roughly the past forty years. The researchers created a customized model for each species to establish its level of sensitivity and exposure to climate. Sensitivity was based on how fluctuations in seasonal temperature and precipitation influenced year-to-year shifts in population size. Exposure was quantified from the longer-term shifts in population due to changes in the preferred climate conditions of each species—in other words, it accounted for how much each species was exposed to the types of changes that appear to matter to it. After establishing these models, the researchers analyzed the degree to which the butterflies' and moths' responses to climate change could be attributed to their exposure and sensitivity to climate.

Using this model, the team was able to explain about 60 percent of the variation observed in British butterfly and moth populations since the 1970s. That is, the preferences of individual species for certain temperatures and precipitation levels during particular seasons, along with how the changing climate has affected those preferred conditions, have shaped the insects' reactions to climate change. While some species have benefitted from the warming British summers, conditions have actually worsened for half of the butterflies and moths, whose populations have instead declined. The researchers conclude that variation in species' responses to recent climate change may be more predictable than previously recognized. (*Science Advances*)

—Ashley Braun

The Right Vibes

Choosy females are a driving force of evolution, with their pickiness sometimes resulting in a single species splitting into two or more distinct ones. Females often assess male attributes of color, sound, and chemistry, but new research on bees elaborates the importance of tactile vibrations too.

In the red mason bee (*Osmia bicornis*), females prefer males that vibrate for the longest time. This finding was established in 2010 by a team that included research scientists Taina Conrad and Manfred Ayasse, at the University of Ulm, Germany. Sustained thoracic vibration is presumably a telling indication of male bee fitness, "because the vibrations are produced by contracting wing muscles, which uses energy," explains Conrad. But the team also discovered that female bees from the United Kingdom, Germany, and Denmark strongly prefer males from their own region. Conrad and Ayasse wondered why.

TAINA CONRAD

A precopulatory pair of German red mason bees

After using a laser vibrometer to characterize the regional vibrational signals of male bees, Conrad and Ayasse investigated these indicators' influence on female choice. A lightweight magnet was glued to a male bee mid-section so that its vibrations could be manipulated without altering its chemical cues. Once a magnetized male paired up by landing on the back of one of ten females in a flight cage, the couple was placed over an inductor that used an electromagnetic field to control the male's vibrations.

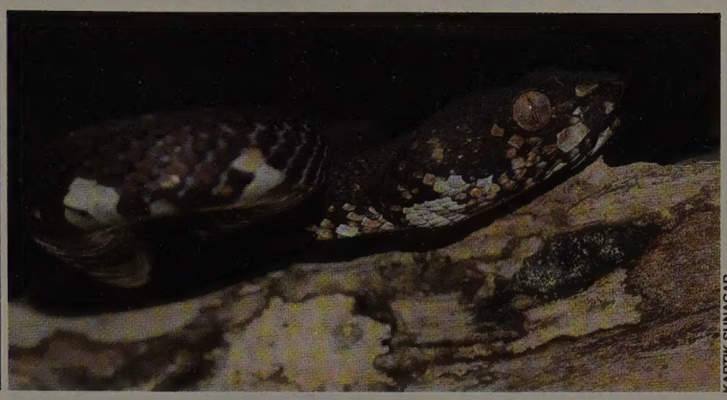
Male bees from England and Germany could be made to vibrate like those from their own or from the other country.

It turned out that female bees from the English population were more willing to copulate with males vibrating in the English style, whether those bees were English or German. The same was true of German female bees tested for their preference for English versus German males.

This research suggests that females favor males with familiar, local vibrations. Imported bees—even of the same species—have subtle differences that will influence breeding success and their sustained availability for pollination. Moreover, if red mason bees only mate with others from their own region, new species best suited to each location may arise. The study of vibrational communication is "in its infancy," says Conrad, yet it has important implications for species' maintenance and evolution. (*Current Biology*)

—Lesley Evans Ogden

YEHU MORAN



KARTIK SUNAGAR

*The starlet sea anemone (*Nematostella vectensis, left*) comes from an ancient venomous lineage, whereas Anderson's pitviper (*Trimeresurus andersoni, right*) represents a venomous lineage that has evolved more recently.*

Chemical Warfare

Venoms, the debilitating chemical cocktails animals unleash to defend themselves or obtain a meal, are subject to an evolutionary arms race. Those creatures that are targets of toxins eventually develop beneficial mutations, granting them some degree of resistance. In response, animals that dole out venoms undergo changes so their poisons remain effective.

This tit-for-tat narrative of venom evolution is incomplete, however, as evolutionary biologists Kartik Sunagar and Yehu Moran of Hebrew University in Jerusalem have shown in a new study. They realized that many venom studies have focused on snakes and cone snails—comparatively "young" animal groups, evolutionarily speaking, only going back roughly 50 million years. Over these groups' histories, their venomous arsenals have expanded considerably, bolstering the arms race analogy, also known as positive, or Darwinian, selection.

Sunagar and Moran cast a wider net, looking at over 3,500 gene families for venom production in newer and older animal groups. The ancient animal types included spiders, scorpions, centipedes, octopus, squid, jellyfish, and sea anemones.

The scientists found that these ancient animals exhibited surprisingly low levels of genetic variation in their venoms. Sunagar and Moran reasoned that the venoms of primordial creatures had undergone substantial negative, or purifying, selection—evolutionary pressure to keep their potently optimized toxins roughly the same. "Negative selection filters out certain mutations that alter structure or function," explained Moran. For species in long-established ecological niches, it makes sense to maintain what works.

Evolution does favor bolder experimentation, though, when creatures enter new habitats and begin adapting to the novel environment. As they find their place in local food chains, venomous animals' toxic pharmacopeia should undergo rapid diversification—the better to catch strange new prey and withstand the attacks of previously unencountered predators. Yet over time, these adapting species settle into tried-and-true formulae.

The researchers dub this model of venom evolution "two-speed," with the venoms of old species evolving slowly and those of new species evolving quickly. "Our analysis of numerous toxin families, spanning the breadth of the animal kingdom, has revealed a striking contrast between the evolution of venom in ancient and evolutionarily young animal groups," said Sunagar. (*PLOS Genetics*)

—Adam Hadhazy

Super Duck

Along the border between Montana and Alberta, Canada, lie 70-million- to 85-million-year-old rock formations rich with fossils. In 1936, researchers digging in the Oldman Formation of Alberta found bones belonging to *Brachylophosaurus canadensis*, a species of hadrosaur, or duck-billed dinosaur. Notably, *B. canadensis* has a paddle-shaped crest on its skull. In 1999, researchers excavating the nearby Two Medicine Formation of Montana found an older relative of *B. canadensis*, which they later named *Acristavus gagslarsoni*. This species lacked the prominent crest of *B. canadensis*, raising the question of when and how the duck-billed dinosaurs acquired their crests.

SEPP JANNOTTA, MSU NEWS SERVICE

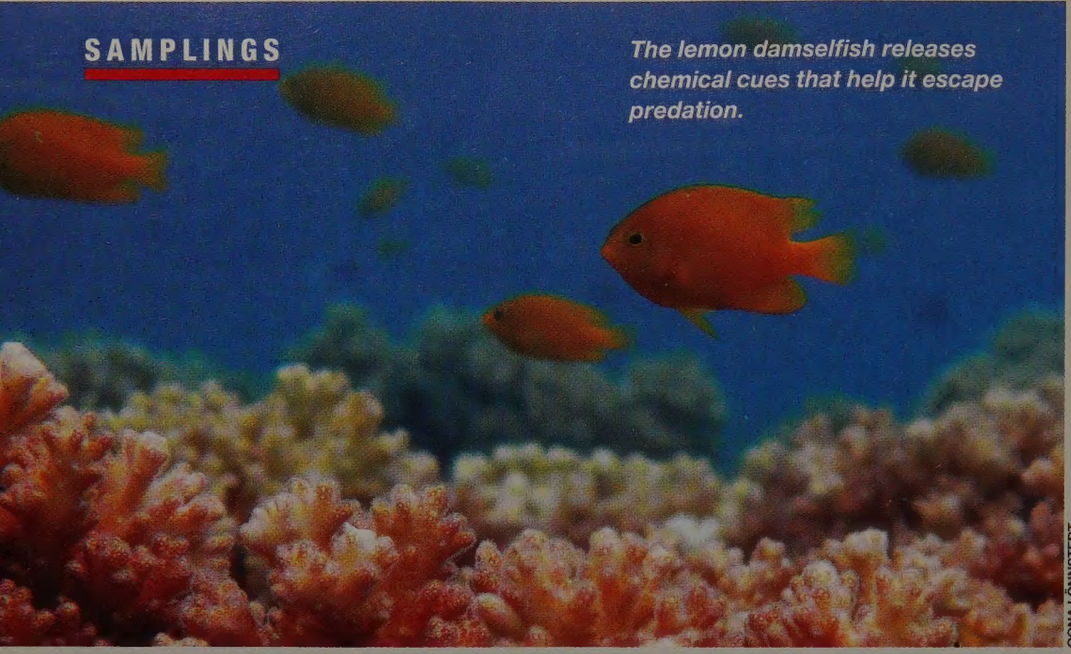
Paleontologist Elizabeth Freedman Fowler holds an artist's rendering of the newly-discovered dinosaur P. bergei.

A team of researchers led by Elizabeth Freedman Fowler of the University of Montana and John R. "Jack" Horner of the Museum of the Rockies in Bozeman, Montana, recently discovered a fossil that may fill this gap. In the Judith River Formation in Montana, deposited after the Two Medicine Formation and before the Oldman Formation, they uncovered and identified 79-million-year-old bones of a new duck-billed dinosaur. They named the species *Probrachylophosaurus bergei*—*Probrachylophosaurus* since it came before *Brachylophosaurus*, which itself means "short-crested lizard," and *bergei* in memory of Sam Berge, who co-owned the land where the dinosaur was found. This new species has a smaller crest than *B. canadensis*.

Nicknamed "Super Duck," *P. bergei* weighs in at about five tons and stretches thirty feet from head to tail. It is larger than any found specimen of *B. canadensis*, indicating that the new fossil was not simply a juvenile of that species.

The discovery of a small-crested intermediate species provides clues about how crests evolved in hadrosaurs. Researchers think the small crests of *Probrachylophosaurus* gradually became larger over many generations through a process known as heterochrony—a change in the timing or rate of crest development in juvenile dinosaurs. The crest, found in both males and females, was likely an ornament to attract mates, since it would not have been strong enough to be physically functional. (*PLOS ONE*)

—Kati Moore



The lemon damselfish releases chemical cues that help it escape predation.

OONA LÖNNSTEDT

Damsels in Distress

The lemon damselfish (*Pomacentrus moluccensis*) spends its life amidst the vibrant coral of the Great Barrier Reef, Australia, feasting on plankton and tiny shellfish. Although it can also find itself in the jaws of larger predators, such perilous situations are not always fatal. When a damselfish is bitten, specialized cells in its skin release an alarm chemical. The substance not only warns fellow damselfish to stay away, but a new study by marine biologists Oona M. Lönnstedt, now at Uppsala University, Sweden, and Mark I. McCormick, at James Cook University, Australia, suggests the chemical attracts secondary predators. These kleptoparasites come looking for an opportunity to steal prey from the first predator. Having seen many juvenile reef fish with scars, the researchers wondered whether secondary predators create diversions that increase the chances a damselfish might escape.

The scientists tested their hypothesis in two ways. In the wild, they made timed releases of damselfish chemical alarm cues and of seawater controls into the water around a reef in the home range of individual dusky dottybacks (*Pseudochromis fuscus*), which are very territorial predators of juvenile damselfish. The dottybacks increased their activity levels when alarm cues were released and spent a greater proportion of their time within the vicinity of the cue source outlet compared with fish exposed to control cues. The alarm cues also attracted additional dottybacks, as well as an assortment of other predatory species, to the home range.

Next, the researchers set up a laboratory aquarium in which dusky dottybacks were given access to lemon damselfish. When just one dottyback was present, it almost always caught and ate the damselfish. However, when a second dottyback was introduced into the aquarium, the first dottyback often released its prey. The damselfish were able to escape more than a third of the time after a secondary predator arrived.

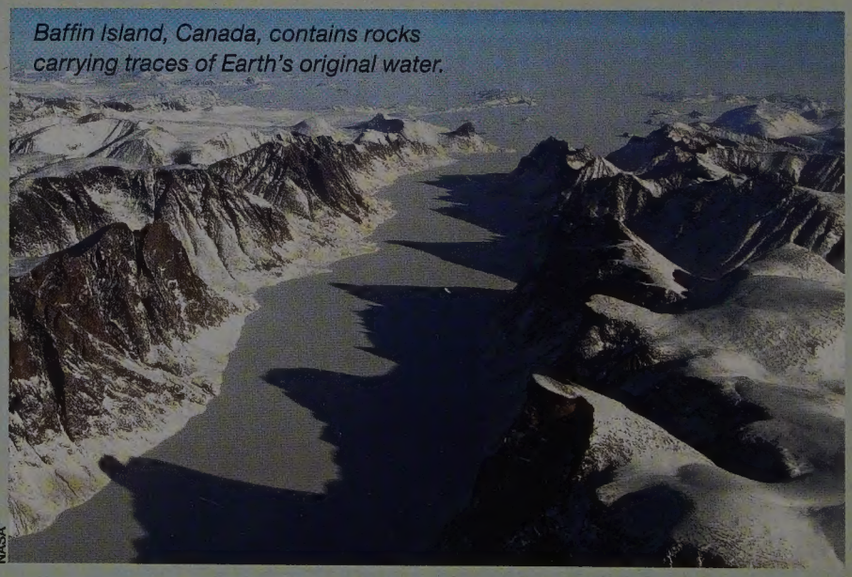
Together these results indicate that damselfish chemical alarm cues function to attract secondary predators, which improves the damselfish's odds of survival. Lönnstedt says the finding demonstrates how critical chemical cues are in coral reef environments. "Now that coral reefs are dying, the degrading coral is masking these cues," she says, and this is interfering with predator-prey interactions. "It's another incentive to protect these habitats." (*Proceedings of the Royal Society B*) —*Niki Wilson*

Primordial Water

Where did Earth's abundant water come from? One hypothesis has been that it was deposited after the planet had formed, by hydrogen-bearing planetisimals or comets that constantly impacted Earth during its early years. But new research suggests that much of Earth's water was present while the planet was in formation.

When cosmochemist Lydia J. Hallis, now Marie Curie Research Fellow at the University of Glasgow, Scotland, was a postdoctoral fellow at the University of Hawaii NASA Astrobiology Institute (UHNAI), she led a team of colleagues that studied selected basaltic rocks from Iceland and from Baffin Island in the Canadian Arctic. They were seeking traces of ancient water. These rocks originated in Earth's deep mantle and have been untouched and mostly unexposed to the elements for 4.55 billion years. The researchers determined the ratio of normal hydrogen to the isotope deuterium, or "heavy" hydrogen, in the water extracted from the rocks, to identify its origin. Water from various sources within the solar system contains differing percentages of deuterium.

The rock analysis utilized new technology that avoided introducing external water. The samples were mounted on indium metal, polished without using water, and stored in a vacuum oven. At the heart of a suite of instruments, an ion microprobe produced a very high vacuum to avoid contamination by atmospheric hydrogen. The instruments allowed the scientists to collect data from an area of just 8 microns (0.0003 inch) in diameter within glassy inclusions in the rock samples.



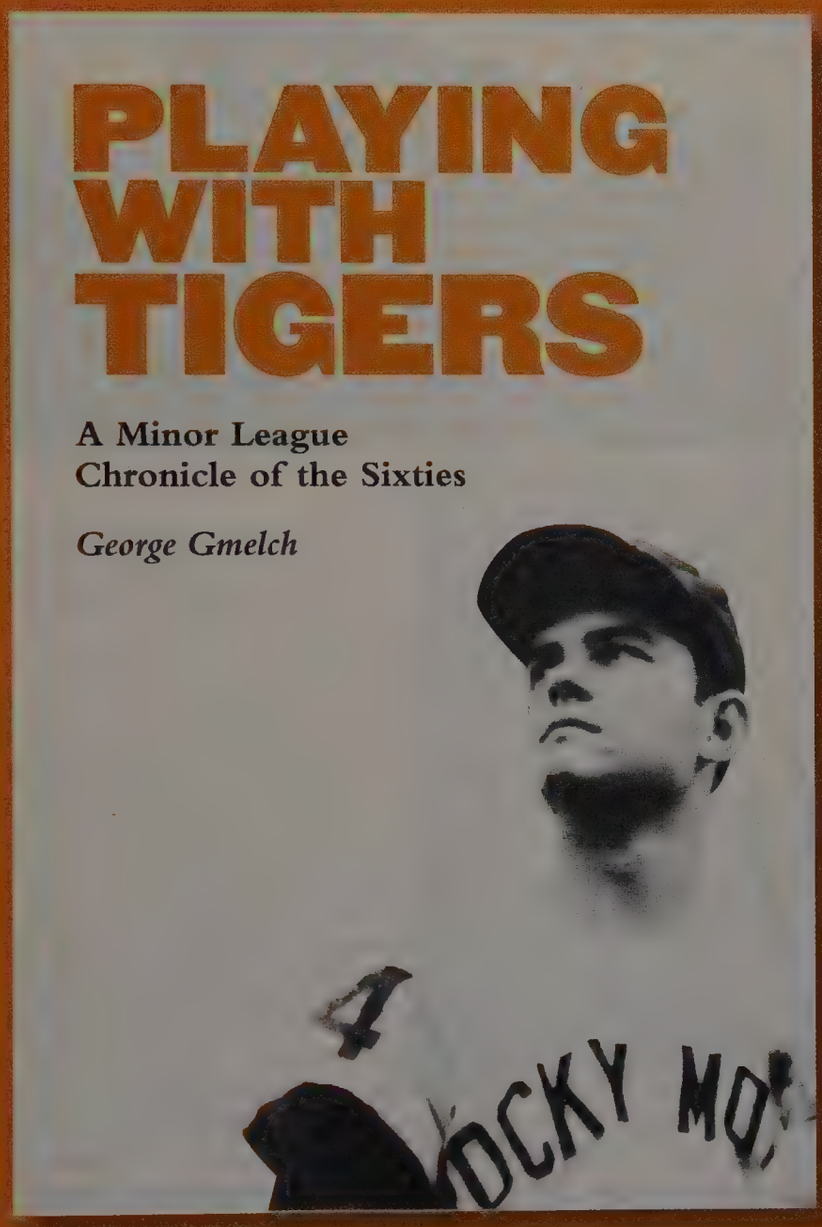
Baffin Island, Canada, contains rocks carrying traces of Earth's original water.

NASA

The water samples proved to contain very little deuterium, which Hallis says "strongly suggests that it was not carried to Earth after it was formed and cooled." The likely explanation is that water was already present in the dust bands that encircled the young Sun and eventually accreted to form Earth and the other planets of our solar system.

Hallis notes that additional data will be needed in order to determine the exact percentage of Earth's current water that has been here since the planet's formation, because it is unknown how representative the studied rocks are of Earth's deep mantle as a whole. (*Science*) —*Harvey Leifert*

A BALLPLAYER LEARNS ABOUT RACE, CLASS, AND AMERICA



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George Gmelch is a professor of anthropology at the University of San Francisco and at Union College, is the author of a dozen books, including *Inside Pitch: Life in Professional Baseball* (Bison Books, 2006). He has written numerous articles for *Natural History*.

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COSMIC BACKGROUND BY MARCIA BARTUSIAK

The Cosmic Poltergeist

Catch-as-catch-can

Aurora Australis over the IceCube Neutrino Observatory at the Amundsen-Scott South Pole Station in Antarctica

Deep beneath the South Pole, thousands of detectors, set within a cubic kilometer of ice, lie in wait. While looking up toward the surface, they also peer downward, hoping to catch certain elementary particles from the northern sky that travel through the Earth daily. Nearly all of these elusive particles—called neutrinos—blithely pass through our dense planet like ghosts on the run. Most of the time no signal is registered by the instruments. But on rare occasions a neutrino and a detector collide.

Between 2010 and 2013, this frigid array of detectors, known as the IceCube Neutrino Observatory, recorded some 35,000 neutrinos journeying from the north, a miniscule number compared to the trillions that traversed the Earth over that time. Most of the recorded neutrinos were generated as cosmic rays impacted the northern atmosphere. But a tiny fraction of them appeared to have arrived from events far outside the Milky Way—from either massive stars exploding in distant reaches of the universe, or from the active cores of blazing galaxies. The particles' ultra-high energy, far beyond the levels of the other neutrinos, revealed them for what they were.

With this success at identification, the IceCube detectors offer an entirely new way to survey the cosmos, an endeavor that couldn't have been imagined less than a century ago. Indeed, the very idea of the neutrino was first thought too crazy to be true, the physics equivalent of unicorns or elves. Even more peculiar was where the neutrino's story began: in a German prisoner-of-war camp during World War I.

The British physicist James Chadwick had been studying the phenomenon of radioactivity in Berlin under Hans Geiger (of Geiger counter fame) when the war broke out. Chadwick was soon sent to an internment camp set up at a racecourse just outside the city. To while away the hours of confinement, he began teaching physics to his prison-mate Charles Ellis, a young and sociable cadet from Great Britain's Royal Military Academy who had arrived in Germany on holiday just before the war's unexpected eruption. Together, the two compatriots organized a small research lab in one of the horse stables, an endeavor that was surprisingly tolerated by the camp's senior officials and generously supported by Chadwick's former German scientific colleagues.

The experience hooked Ellis. After the war, he committed to a career in physics instead of the army and ended up conducting experiments at the famous Cavendish Laboratory in Great Britain, where he studied a troubling anomaly. Whenever a radioactive nucleus decayed by ejecting an electron, something went awry. Ellis and a colleague noticed that the energy of the nucleus before it radioactively decayed was more than the energy of the system afterward (that is, the combined energy of the depleted nucleus and the fleeing electron). It looked as if energy were disappearing, which violated one of the most sacred rules of physics—conservation of energy. Energy can neither be created nor destroyed.

But Wolfgang Pauli, a Viennese physicist, had an abiding faith that atoms were obeying the physical laws of the land, which led him to a radical proposition. In 1930, he suggested that an entirely new particle, invisible to ordinary instruments, could explain

the energy discrepancy. Every time a nucleus spewed out an electron, it also emitted a neutral, phantom-like particle that seemed to vanish, carrying away that extra bit of energy and balancing the books.

Usually undaunted by new concepts, Pauli was intimidated by the outrageousness of this idea. "Dear radioactive ladies and gentlemen," he teasingly wrote his friends, then attending a physics conference in Germany. "For the time being, I dare not publish anything about this idea and address myself confidentially first to you, dear radioactive ones, with the question of how it would be with the experimental proof of such a [particle]." He thought of his remedy as "desperate." It wasn't traditionally acceptable for theorists to conjure up particles out of whole cloth, especially particles that seemed impossible to catch.

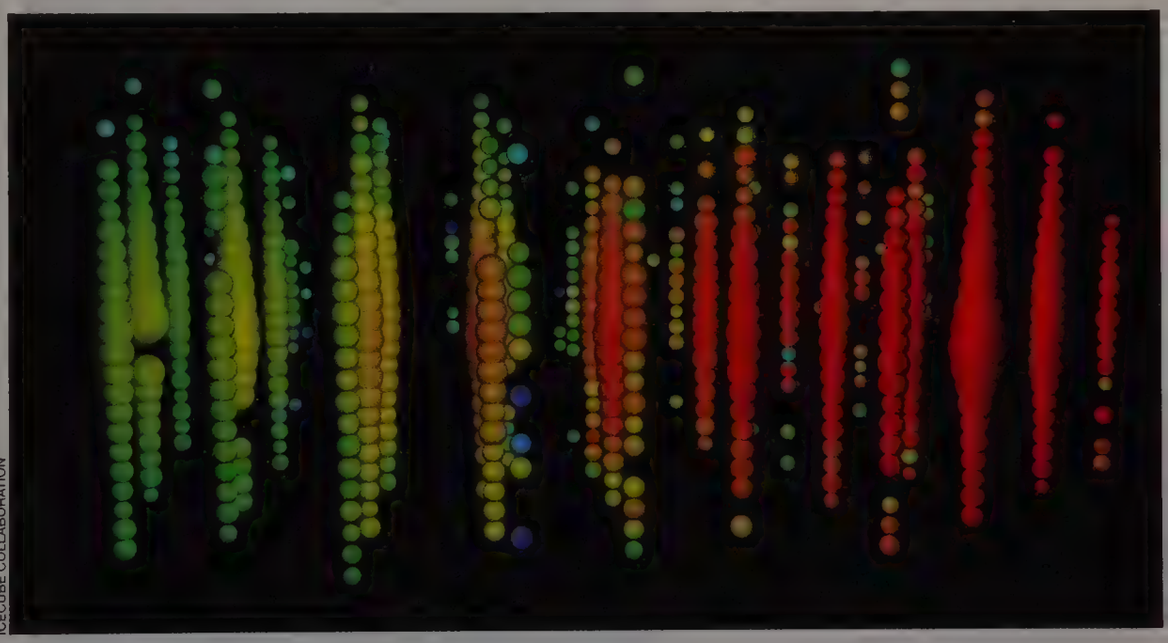
Not until Chadwick discovered the first known electrically chargeless particle—the neutron—in 1932 did Pauli at last get the courage to officially publish his idea. Soon after, physicist Enrico Fermi dubbed Pauli's hypothetical particle the neutrino, Italian for "little neutral one." The name was apt, for at the time the neutrino was thought to have no mass. According to Pauli's theory, it was nothing more than a spot of energy that flew off at the speed of light.

Despite Chadwick's discovery of the neutron, it took years to prove that neutrinos were more than figments of Pauli's imagination—so long, in fact, that some physicists began to call his particle "the little one who was not there." Pauli had reason to be apprehensive. The neutrino is so oblivious to ordinary matter that it would take a stack of lead, thousands of light-years in length, to stop one in its tracks. Neutrinos bolt through the Earth as if it's no more substantial than a cloudy mist.

But the odds of catching one are considerably increased if there is a flood of such particles coming at you. Indeed, that's how they were finally cornered. In the mid-1950s, physicists Clyde Cowan and Frederick Reines set up a detector outside a South Carolina nuclear power plant and each hour caught a few neutrinos out of the trillions generated by the reactor's core. Receiving news of the verification while attending a conference in Zurich, Pauli celebrated with colleagues by climbing the town's local mountain and enjoying several wine toasts at the top. With a friend on each arm helping him on the way down, Pauli turned to one and remarked, "All good things come to the man who is patient."

About a decade later, physicist Raymond Davis set up the first neutrino observatory in a gold mine, nearly a mile beneath the Black Hills of South Dakota. An underground location assured the measurements would be free from disruptive cosmic rays. In continuous operation for a few decades, Davis's detector kept watch on the torrent of neutrinos flung into the solar system as the Sun burned its nuclear fuel. It provided the first hint that the neutrino had a smidgen of mass after all. More advanced underground observatories constructed in the 1990s provided the ultimate proof, a confirmation that won the lead researchers for the experiments—Takaaki Kajita at the Super-Kamiokande detector in Japan and Arthur McDonald at the Sudbury Neutrino Observatory in Canada—the Nobel prize in physics just last year.

Neutrino detectors and observatories can now be found or are under construction around the globe: not only in Antarctica, Japan, and Canada, but also in France, Russia, Italy, and India. And they are beginning to extend their searches beyond the neutrinos emanating from the Sun to the more powerful particles trekking through the cosmos. While weighing less than a billionth of the mass of a proton, each neutrino we are able to capture will help scientists understand the universe's history, structure, and future fate.



ICECUBE COLLABORATION

In October 2010, a high-energy neutrino crossed a detector at the IceCube Neutrino Observatory, leaving this track of light.

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Woolly and Wondrous

Conspicuous cover

In early November, I saw a white dot drifting and hovering around me. It shone pure white against the dark forest background. There was not a breath of wind, but the dot was moving to the right, to the left, up, down. Mesmerized by this shiny white miniscule that was obviously self-propelled, I looked around and saw another, and another, and after some minutes, yet another. Because of my proximity, I knew these white dots were much smaller than the noctuid moths that fly at night or the frail geometrid moths that flutter weakly both at night and in the day at this time of year. The white dots were too small for me to see wings, but by their behavior I concluded they had them; they could only be insects. I waited for others to come near and succeeded in grabbing three. There was not much to see in my hand afterwards, only tiny wings and a small stain of dark mush—enough, however, for me to see that they were aphids. Aphids flying? And flying in November, when there is frost every night and the chance of snow?

The vanishing white layer told me they must be woolly alder aphids (*Prociphilus tessellatus*), which are covered with delicate slender filaments of white wax. Aphid clusters attach to alder twigs, where they look like a cushion of snow, or perhaps a mushroom or mold that infects the twig. Woolly alder aphid colonies are not uncommon in this part of Maine. I soon found a cluster, about four or five centimeters long. Within clusters, aphids are closely packed and spend all winter on twigs exposed to the elements. In the summer, the aphids are protected by ants that milk them for honeydew by stroking them with their antennae, which causes the aphids to release an anal secretion that is a filtrate of plant juices. Aphids need amino acids to make protein, but when they suck juice from twigs they also get a surplus of sugar that is not needed for their low-energy, sessile lives, effectively glued to one spot generation after generation.

Woolly aphid colony under their own secretions

ALL IMAGES BERND HEINRICH

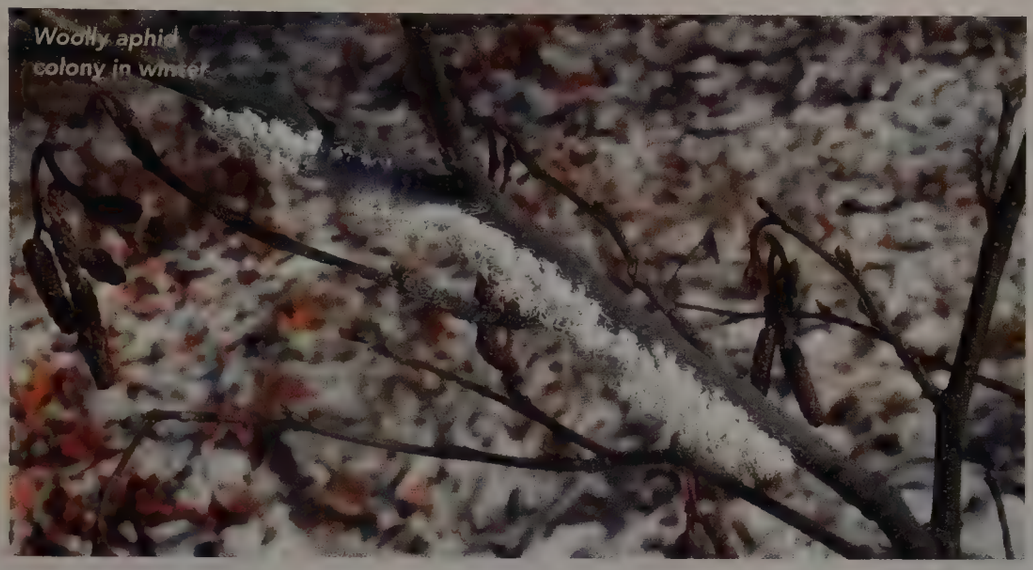
For as long as I can remember, I have routinely seen white patches of seemingly comatose aphid colonies stuck to twigs, and I've paid them little attention. But the white, cottony, winged tufts that were wafting about me in November provided a glimpse into what might be an exciting story.

I brought my now-valued specimens—three squashed aphids carefully placed into a piece of notepaper in my pocket—back as treasure to my cabin, along with the colony that I had found. With a magnifying glass, I could verify that the flying objects were indeed two-winged aphids. I half-expected others to emerge from the colony and to start flying after they warmed up. I kept the colony in the cabin for a day, but nothing budged. I photographed the colony and disassembled it, finding it consisted of fifteen round squat blobs, all wingless dark blue aphids with legs so tiny they could not possibly be useful, even for crawling. These blobs were huge in comparison to the winged forms I had caught the day before. When I peeled away the white, stringy, waxy coverings, I found twenty-two almost microscopic wingless miniature aphids with legs. These nymphs, all of the same size, were probably recently born (or hatched).

All of the big, round, wingless aphids must have been adult females, who throughout summer and early fall were participants in the curious asexual (parthenogenetic) life cycle of aphids. After many generations of virgin births, however, aphids produce nymphs that undergo a physiological change: they grow wings and become sexual. Changes in the environment may trigger the response—shorter day lengths, cooler temperatures, or reduced food supply. It was these seldom-encountered winged and sexual aphids that I had seen and caught.

The winged aphids may not have

issued from the colony I found—but they would have been from one like it and were probably born several weeks earlier. They had been, and maybe still were, looking for mates or a place to overwinter, and, if female, possibly looking for another alder on which to attach and become a colony-mother, ready to restart the life cycle in the spring. That is the story of such aphids.



I might have let it go at that. But then I realized something odd. The colony that I had pulled apart on this November day had *already contained a batch of babies*, and the winged (final sexual and dispersal) forms were simultaneously present in the field. Those babies, come next spring, would *not* be able to disperse. They would attach to the alder twig where their mothers, and their grandmothers, and their great-grandmothers, had grown up. This means that the colony is not an ephemeral entity; it is a multi-year community, which periodically sends out sexual propagules to establish colonies elsewhere. If so, what is the point of maintaining a colony in the winter? Why could the woolly aphids not be like other aphids, semi-communal at times simply from the incidental clumping due to adults' parthenogenetic reproduction at the same spot? These aphids were clumped together into an apparently deliberate tight package, which was all the more a community because their dense cover of white wax obscured the individuals. I had routinely seen them in past winters, never suspecting they contained nymphs.

Spurred on by my find of youngsters in the midst of what would normally be the end of the annual aphid cycle, I had a newfound interest in woolly aphids. The next day, I kept my eyes open for colonies. With the search image in my mind, I almost immediately found one colony after another—a total of thirty-two. A pattern jumped out at me. Although only one colony generally occupied each clump of alder bushes, there was often another colony close by. In one of my finds, the alder bush had ten colonies. Based on the six colonies that I picked apart, the number of aphids per colony ranged widely from nine to 213. None contained winged forms but all contained approximately twice as many nymphs as adult females. All of the nymphs were of the same, almost microscopic, size. These data reinforced the notion that colonies grow over a timespan much longer than just one season. But why do they persist? Does the white fluffy wax have something to do with the pattern? For this unusual wax to have evolved, it must provide some advantage to the aphids. What could it be?

The fact that the wax hides the plump aphids is probably not incidental. I saw no evidence that any colony had been ripped apart. The white material may indeed be perceived to be so different from birds' usual prey that it is ignored. And if not, and a bird did pick at an aggregation, it would first taste wax and be put off. I licked an aggregation: the wax was flavorless and is unlikely to be toxic. However, that it offers protection from predation is shown indirectly by the caterpillars and lacewings that have evolved to prey on aphids within the colony—they use the wax to camouflage themselves.

The second not unrelated possibility for maintaining a colony in winter involves the babies found overwintering within the colony. They were in the interstices among the adult aphids, and the whole colony was uniformly covered with the wax. Thus, the colony seems to be a secure home that may help protect the young, and perhaps give them a head start in the spring.

It may seem ironic that the highly conspicuous wax, which makes the woolly aphid colony easy to spot, should be a defense against predators. Charles Darwin had pondered why prey species are sometimes so eye-catching, and it had long been an enigma. We now see it as aposematic, or warning, coloration—just as bright and colorful markings distinguish noxious insects, which a predator will soon learn to avoid, the bright white may serve as a reminder that aphids do not taste good. Alternatively, when seen from a distance, the white may mimic snow or mold, which does not warrant a closer look. But I took a closer look. And I saw something quite intriguing: both baby and flying woolly aphids in November, giving me new appreciation for these wondrous winter colonies.

Bernd Heinrich is a biology professor emeritus at the University of Vermont. He has published numerous books, most recently The Homing Instinct: Meaning and Mystery in Animal Migration *(Houghton Mifflin Harcourt Publishing Company, 2014).*

The Northern Elepl

An alpha male vocalizes to keep rivals away from his harem.

nt Seal

CAROLYN CAMPBELL

The biochemistry of this marine mammal may hold clues to better human health.

By Carolyn Longstreth

On a gray, drizzly February day in Northern California's Point Reyes National Seashore, a female northern elephant seal *(Mirounga angustirostris)* is in labor on North Drake's Beach, a narrow patch of sand between the bay and the steep cliff rising behind. A dozen or more gulls jockey for position around her, ready to snatch up a morsel of fresh placenta. Three enormous alpha males guard their harems, keeping a watchful eye on the subordinate males sleeping on the edge of the colony. Other newborn seals are nursing and squealing to keep in contact with their mothers.

Tourists gather on an observation platform nearby. They coo at the newborn pups and watch awestruck when the big, captivating males begin to fight. But probably few if any of these human observers comprehend the extraordinary physiology of northern elephant seals.

The adult males begin to appear on Point Reyes beaches in December. Right away, the largest set out to intimidate potential rivals. The males are huge, often weighing over 5,000 pounds. Endowed with large canine teeth, leathery chest shields and the thick, fleshy snout that gives the species its name, the alpha males spend the next two and a half to three months posturing, trumpeting, and even physically attacking other males, all to prevent other contenders from approaching their harems. In an astounding feat of endurance, adult male elephant seals survive the entire breeding season without any nourishment or water.

The females' arrival is staggered over the next two months. Each settles into a harem to give birth and nurse her pup. For thirty days, she, too, fasts while providing the newborn with milk that is one of the richest known. High in both protein and fat, it gradually thickens to the consistency of ketchup. The pup, sixty to seventy-five pounds at birth, grows to a blubbery three hundred pounds by the end of the month.

But the pup's gain is the female's loss: she drops one-third or more of her body weight, and up to twenty-five percent of her protein. Near the end of the thirty days, her body fat descends from a baseline of thirty-four percent to the intolerably low level of twenty-three percent. At that point, she becomes receptive to breeding. She mates with several males and returns to sea, abruptly weaning her pup.

Once the last female has left the beach, the males fol-

SAMANTHA FORD

low. To regain weight and recover their strength, adults of both sexes travel great distances, either to the west or northward along the continental shelf, foraging at great depths for fish, squid, octopus, rays, and crustaceans.

The pups, known as "weaners," stay on the beach unattended for another two months, surviving off the blubber that accumulated during their first thirty days. The young seals can neither swim nor hunt for food at this stage. They seem vulnerable; indeed, elephant seals historically avoided the mainland to protect the newborns from predation by grizzly bears.

JACOB HARRIS

A male inflates his large snout with air to amplify the vocalization.

Nowadays, with the extinction of the California grizzly, weaners can be left safely on beaches, where they sleep much of the time. Their lungs, ears, and other organs gradually develop in preparation for the challenge of diving and feeding in the deep. Little by little, the weaners spend more time in the water, learning to swim on their own. By April or May, they venture out to sea, apparently guided by nothing more than instinct. About half survive the first year; less than a third live for three years.

During the nineteenth century, elephant seal blubber, like whale oil, was used for lighting and the species was hunted to the brink of extinction by the late 1800s. Although a tiny remnant population continued to return to Guadalupe Island in Mexico, museum collectors took what survivors they could find while fewer than one hundred seals remained off shore. Eventually, legal protections were put in place by both Mexico and the United States, and, even more fortuitously for the seal, electric lights replaced oil lamps.

The elephant seal population began to rebound. New breeding colonies sprang up in Mexico and along the California coast at the Channel Islands, Año Nuevo, Cape San Martin, the Farallon Islands, and at the Point Reyes National Seashore. The fastest-growing colony in California was established at San Simeon in 1991 by seals that had most likely come from the Channel Islands. A few nonbreeders can also be found further north at Crescent City and even in Oregon. Today, the elephant seal population exceeds 150,000.

Elephant seals belong to a subgroup of carnivores called pinnipeds: marine mammals that, unlike whales and dolphins, lack the ability to give birth and nurse young in the water. Among the pinnipeds, however, elephant seals

are unique in a number of ways. Males and females are so different in appearance that they seem almost to belong to separate species. The adult males are three to five times larger than females. When a bull vocalizes to intimidate a rival, he throws his head back, opens his mouth wide and fills his large nose with blood and air. The inflated snout covers the upper part of the bull's open mouth, amplifying his resonant and explosive trumpeting. Testosterone levels in alpha males are among the highest known in nature during the breeding season but among the lowest the rest of the year.

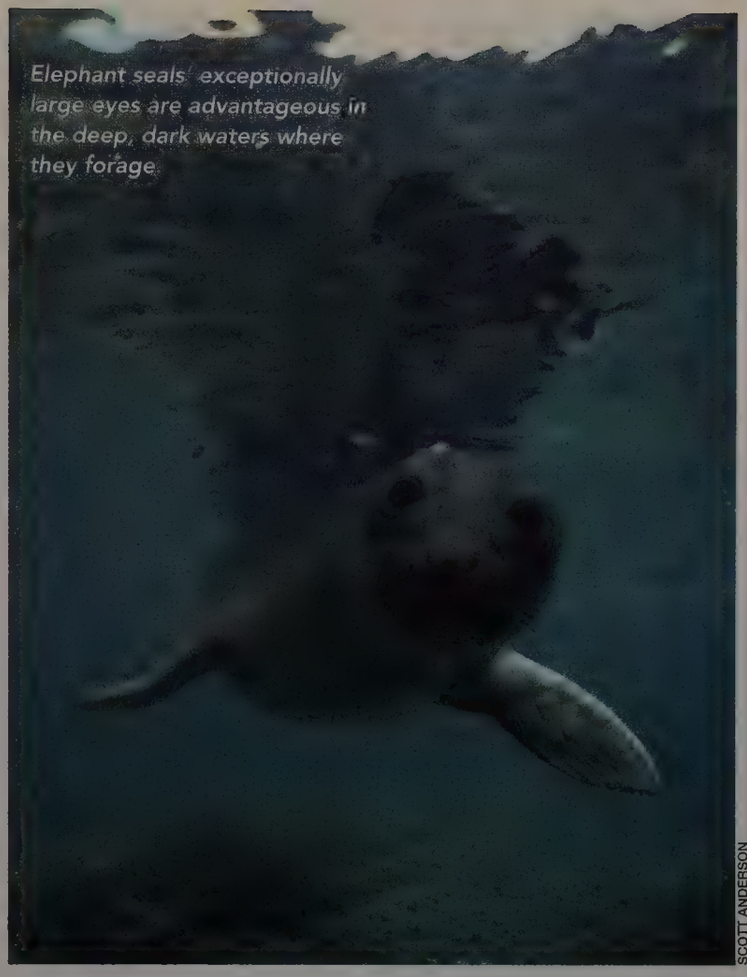
At sea, elephant seals dive deeper and stay underwater longer than all other pinnipeds and most whales. Their exceptional capacity for breath-holding enables these seals to prey on species that other marine mammals cannot reach. With large eyes that can detect bioluminescence, they typically forage at depths ranging from three hundred feet all the way down to the dark, cold, extreme environment at three thousand feet. A microprocessor attached to a seal's back measured the longest elephant seal dive ever documented: 119 minutes. On the deepest dive—recorded in the same way—the seal descended over a mile below the surface.

Such long dives are made possible by physical as well as behavioral adaptations. Just before diving, the seal exhales and retracts its nose into a wedge shape, and the lungs collapse, lessening buoyancy. For the first twenty minutes or so, the seal makes use of oxygen stored in its blood and muscles. The seal's heart rate drops from 115 to as few as three beats per minute and blood migrates to essential organs—the heart and brain. The seal also enlists gravity to increase the efficiency of its descent by alternating drifting with active diving. Once its supply of oxygen is used up, the seal continues to produce energy by switching to an anaerobic respiratory process called glycolysis.

Between dives, elephant seals surface for a much shorter interval than most other marine mammals require to recover from lengthy periods underwater—an average of only three to eleven minutes. In this way, the species is able to hunt for food virtually continuously for months at a time.

Even on land, elephant seals habitually hold their breath for extraordinarily long periods. As their fasts progress, males sleep up to sixty percent of the time, experiencing frequent episodes of apnea or breath-holding lasting as long as eight to twelve minutes. Weaners, as they develop, also regularly hold their breath while sleeping, possibly as much as eighty percent of the time.

Elephant seals even molt their skin and fur in an atypical fashion. Unlike many other pinnipeds that can gradually replace their fur while in the water, elephant seals must return to the shore for a period of three to four weeks, undergoing a radical or "catastrophic" molt. In April and May, females and young adults return to the same beaches that were used earlier for pupping and breeding, while mature males come back to molt in June and July. With two round trips each year from the foraging grounds to the colony site, elephant seals migrate 12,000 to 14,000 miles annually, farther than any other mammal.



Elephant seals' exceptionally large eyes are advantageous in the deep, dark waters where they forage.

SCOTT ANDERSON

Many aspects of elephant seals' natural history were first observed almost 150 years ago. A whaler, Charles Scammon, described the northern elephant seal in an 1874 treatise; Charles Darwin wrote about them three years earlier. By the twentieth century, elephant seals had become one of the most studied of all marine mammals. And with the more recent development of electronic devices and satellite tracking, wildlife biologists have learned even more about the species' seasonal movements and diving.

Researchers are now discovering how elephant seals' unique abilities function at the cellular and even molecular level. Daniel E. Crocker, a biology professor at Sonoma State University, began studying elephant seal metabolism and physiology about fifteen years ago, building on the work of earlier researchers such as C. Leo Ortiz and Daniel P. Costa, both of the University of California, Santa Cruz.

Crocker and his colleagues concentrated on two of the most distinctive adaptations seen in elephant seals—lengthy fasting and prolonged breath-holding. These studies have led to new findings on the biochemical effects associated with these behaviors, findings that help explain how the seals tolerate such extremes and that may someday lead to important medical advances.

Consider the twice-yearly fasting. When they come

ashore to breed or molt, adult elephant seals go as long as three months without any food. Other mammals, such as the black bear, are known to fast during winter hibernation, but these species reduce their need for calories by slowing down their metabolism and sleeping. Females of other pinniped species—Steller's sea lions and northern fur seals, for example—fast after giving birth, but they do so for shorter periods, seven to fifteen days, before they begin to take brief foraging trips.

Elephant seals not only fast for much longer, they remain highly active while doing so. Alpha and subordinate males intermittently chase each other, posture, and fight, all activities that require tremendous energy. As for the females, imagine a mother human lactating and fasting for an entire month! Weaners, for their part, use plenty of energy to grow and develop during the fast. While elephant seals are not as active during the molt as they are during the breeding season, the process of growing new fur and skin on the entire body also consumes considerable energy.

Crocker and his colleagues wondered how elephant seals are able to endure their long fasts. As they worked to tease apart this phenomenon, they discovered that, as with humans afflicted with type 2 diabetes, fasting elephant seals experience both high levels of blood sugar and insulin resistance. This condition was puzzling because in other mammals, it is eating rather than fasting that causes blood sugar—glucose—to rise. A jump in blood sugar prompts the pancreas to release insulin, triggering a series of reactions that cause an increase in an enzyme known as GLUT4. GLUT4 serves the critical function of aiding the movement of glucose from the blood into muscle and fat cells where it can be used to provide energy. As cells absorb glucose, the level of sugar circulating in the blood returns to its baseline level.

Normal cellular sensitivity to insulin is essential for this metabolic process. In humans, when cells become desensitized or "resistant" to insulin, the process goes awry, causing a decline in the supply of GLUT4, which reduces the movement of glucose into cells and leads to the pathologies associated with type 2 diabetes, including damage to the heart, kidneys, eyes, and nerves.

Remarkably, fasting elephant seals fail to develop these complications. Furthermore, GLUT4 *increases* despite the seals' impaired sensitivity to insulin, suggesting that insulin-resistant elephant seals have an alternative way to produce this essential enzyme. Indeed, further experiments revealed that another enzyme, AMPK, also increases in fasting elephant seals. Because AMPK promotes the activity of GLUT4, the researchers inferred that elephant seals are capable of marshaling AMPK, instead of insulin, to stimulate the action of GLUT4, easing the movement of glucose into cells and lowering blood sugar levels enough to avoid the pathologies of type 2 diabetes.

Elephant seals' ability to produce GLUT4 without normal insulin signaling is virtually unique in the animal world. The discovery raises hopes that Glut 4 in insulin-resistant humans can be activated by AMPK or some other means, thereby reducing blood sugar and helping diabetics to dodge the serious complications of the disease.

An alpha bull meets a challenger at the water's edge

JOHN LONGSTRETH

The researchers also wondered whether elephant seals' prolonged breath-holding while sleeping and diving might increase their risk of a type of cellular damage known as oxidative stress. In all mammals, the chronic alternation of normal breathing and apnea sets off chemical processes that release unstable particles called radicals or oxidants. These particles bombard nearby molecules in an attempt to form a stable compound, inflicting damage to cells. Oxidative stress increases with age, leading to unhealthy inflammatory processes and, in older humans, greatly contributing to the development of heart disease, Alzheimer's and Parkinson's diseases, cancer, arthritis, and many other conditions.

SCOTT ANDERSON

An elephant seal undergoing catastrophic molt

Fortunately, humans and other mammals have natural defenses against this kind of damage, including the antioxidant molecules known as vitamin E, vitamin C, catalase, and glutathione, as well as gene-regulating proteins called SODs, Nrf2, and HIF-1.

Oxidative stress is aggravated not only by apnea but also by fasting. With their propensities for both behaviors, elephant seals, as would be expected, show a greater capacity to produce harmful radicals than non-diving mammals. Yet they do not exhibit more oxidative damage in their tissues than terrestrial mammals.

Investigating further, Crocker and his colleagues discovered two processes that counteract oxidative stress in elephant seals, one triggered by apnea, the other by fasting. More specifically, they found that while apnea increases the production of radicals, it simultaneously promotes a dramatic increase in the antioxidants SOD1, catalase, Nrf2, and HIF-1. Similarly, elephant seals' fasting stimulates the production of radicals but at the same time ramps up the secretion of the powerful antioxidant enzyme glutathione, doubling it in red blood cells and quadrupling it in muscle tissue.

So both breath-holding and fasting in elephant seals strengthen the antioxidant defense systems even as they promote the production of radicals. The net result is a rough balance between pro– and anti-oxidant activity that gives the seals an enhanced resistance to cellular damage caused by oxidative stress.

Might these findings lead to the development of new therapies for reducing oxidative stress and inflammation in humans? If so, they would represent a potentially major breakthrough in the prevention of heart disease, cancer, Alzheimer's disease, and other age-related conditions. Currently, doctors advise us to eat more fruits and vegetables for their antioxidant properties, but perhaps, with a deeper understanding of how elephant seals prime their natural oxidant defenses, medical science might develop therapies that would help humans to strengthen their resistance to oxidative stress in a similar way.

Other potential clinical applications of elephant seal physiology could also be in the offing. For example, blood oxygen drops to zero during elephant seals' deep dives, yet tissue damage does not occur. Might this phenomenon help us prevent harm to heart muscles during heart attacks, when oxygen cannot reach the heart? Could the seals' capacity for rapid skin growth during catastrophic molt lead to improved treatments for burn victims? Elephant seal blood contains as many as 127 unknown compounds, compared to about five in the blood of a mouse. Science has yet to reveal what purposes they serve or how they might be put to medical use.

Over the past century, the relationship between humans and elephant seals—along with other marine mammals—has undergone a striking about-face as cultural attitudes and new laws followed technological change. Now, instead of hunting them for blubber, thousands of us gather on the shore during the winter months to watch in awe as they fight for dominance, throw back their heads to trumpet, nurse their young, and mate. If the elephant seal's unique physical traits can be translated into treatments for type 2 diabetes, cancer, arthritis, and other age-related conditions, humankind will have further reason to appreciate the species' improbable survival into the twenty-first century.

Carolyn Longstreth is a freelance journalist, birder, activist, and outdoor enthusiast. She is secretary of the California Native Plant Society and serves as a docent for the Point Reyes National Seashore. A founding coordinator of the Point Reyes Birding & Nature Festival, she is the author of the compact disk, "Birding by Ear at Point Reyes."

This article was funded by a grant from the Friends of Natural History Foundation.

Modern Ambiguity

BY LYNN GAMWELL

Mathematics and art are each a paradoxical mix of reality and abstraction.

Before the nineteenth century, premodern mathematicians assumed that geometry and arithmetic had a paradox-free model—the world. When people used arithmetic to count bushels of rice, they applied numbers to tangible objects, whose existence (or absence) is unambiguously clear: the statement "these two bushels and those two bushels make four" refers to a fact in the world-out-there. But once mathematicians began cutting their ties to the physical world in the mid-1800s, the question of the internal consistency of each newly invented axiomatic system loomed ever larger.

© M.C. ESCHER FOUNDATION

M.C. Escher's art often features visual illusions and mirror reflections, such as in his 1935 lithograph Hand with Reflecting Sphere.

German mathematician David Hilbert wrote new formalist axioms for geometry in the 1890s. He declared them complete in the sense that every true statement formulated in elementary geometry could be proven within his system. This is analogous to designing a chess-playing machine that could, in principle, calculate all possible positions in all possible games. Hilbert thus introduced the key distinction between a statement *in* a mathematical system—such as a theorem of geometry—and a "metamathematical" statement *about* a system—such as the assertion that a system of geometry is complete. Twenty years later, Hilbert went on to challenge mathematicians to find the formalist axioms—not just for geometry—but for all mathematics, and to prove their absolute consistency without resorting to a model; in other words, to prove the consistency of the system in the language of the system itself. Proving the absolute consistency of chess would mean developing a way to somehow make assertions about the game (statements in "meta-chess") using only the game's rules and vocabulary—pawns, knights, a sixty-four-square grid, and so on—and to demonstrate that the game's rules do not allow for a contradictory move, such as a pawn being both on and off the same square.

With the emergence of the scientific worldview in the nineteenth century, researchers commonly asked questions about their fields, such as: What are the core assumptions of astronomy? Such questions are, however, peripheral to the field; if an astronomer has a discussion about the nature of astronomy, the scientist is not *doing* astronomy but is engaging in the philosophy of science. Of all the sciences, only within mathematics did such questions about the nature of the discipline come to be posed in its own language. This is possible because mathematical methods can be applied whenever one is attempting a systematic, rational analysis of any subject matter. A mathematician who is doing metamathematics is still doing mathematics, and self-reflection is fundamental to practicing mathematics in the modern era.

SYLVIE DONMOYER

French artist Sylvie Donmoyer (b. 1959) created Still Life with Magic Squares *by painting puzzles and geometric objects against the backdrop of two sixteenth-century publications on mathematics, Albrecht Dürer's* Melencolia I *(1514) and Wenzel Jamnitzer's* Perspectiva Corporum Regularium *(Perspective of Regular Solids, 1568).*

As abstract (non-representational) art emerged in the late nineteenth century, artists self-consciously asked: What is the essence of art? As in mathematics, such questions came to be asked in the vocabulary of art, and by the early twentieth century there was "meta-art"—paintings about the essence of painting and films about filmmaking. The self-reflection inherent in the practice of both modern mathematics and modern art points to a resonance between the two fields.

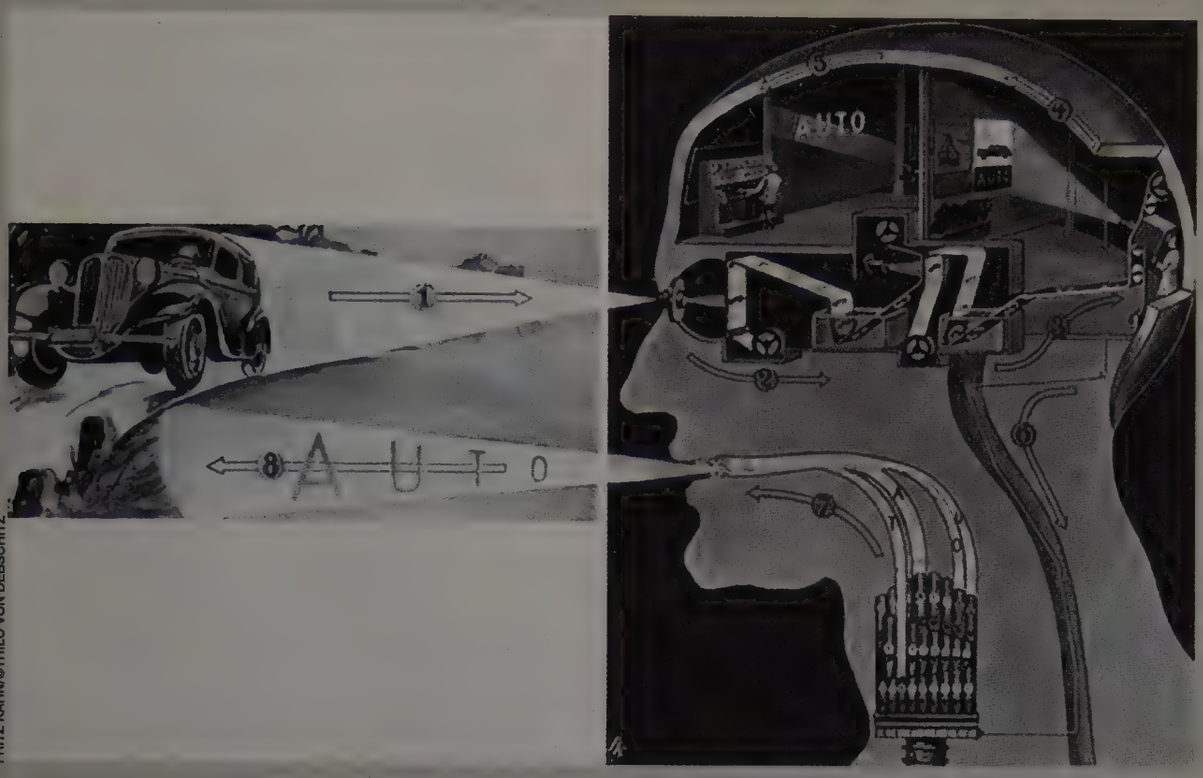
In the early 1920s, during the resurgence of German Romanticism and the soaring popularity of the anti-intellectual Dutch mathematician and philosopher L.E.J. Brouwer, Hilbert had challenged mathematicians to find the one set of axioms that lay at the bedrock of mathematics. Two young Austrians, the philosopher Ludwig Wittgenstein and the mathematician Kurt Gödel, both inspired by Brouwer's critique of formal axiomatic systems, showed that there are truths that lie beyond the limits of natural and artificial languages. To the surprise of many, Hilbert's tower of mathematics founded on absolute certainty was shown to be an impossible dream. The proofs of both Wittgenstein and Gödel relied on the distinction between mathematics and metamathematics, and on the unusual ability of mathematics to describe itself in its own language. As Wittgenstein and Gödel showed, if a natural or artificial language reaches a certain (very low) level of complexity, self-reference is inherent in the system, opening the door to paradox.

Meanwhile, the early-twentieth-century artists Giorgio de Chirico, René Magritte, and M. C. Escher used linear perspective—created in the Renaissance to design or-

XU BING STUDIO AND THE MORGAN LIBRARY AND MUSEUM, NEW YORK

In The Living Word 3, *a 2011 installation by Xu Bing (b. 1955) at the Morgan Library and Museum in New York City, abstract symbols refuse to be systematized. The definition of "bird" is written on the floor in contemporary Chinese, but the characters rise up, become ancient Chinese pictographs based on birds' actual appearance, and fly away.*

dered, harmonious scenes in rational spaces—to construct irrational worlds. Although unaware of Wittgenstein and Gödel's proofs, these artists produced works about enigma and paradox that resonate with these proofs, perhaps because the mathematicians and artists shared common sources in the *Naturphilosophen* Hegel and Schelling (proponents of the Philosophy of Nature), the *Lebensphiloso-*



FRITZ KAHN/©THILO VON DEBSCHITZ

Fritz Kahn portrays language as a completely mechanical or logical process in this illustration of what goes on in our heads when we see an auto and say "auto," from his 1939 publication Der Mensch Gesund und Krank *(Human Health and Illness, Zurich: Albert Müller).*

phen Schopenhauer, Kierkegaard, and Nietzsche (advocates of the Philosophy of Life), and the novelist Fyodor Dostoyevsky, who all argued that there are limits to what can be captured in abstract conceptual systems. These philosophical critiques formed part of the cultural matrix from which Wittgenstein and Gödel emerged to topple the grandest system of all—Hilbert's tower of mathematics.

Hilbert had written his 1899 geometry in a mix of words and mathematical symbols, but with the publication of Bertrand Russell and Alfred North Whitehead's *Principia Mathematica* in 1910–13, he had at his disposal the technical tools of predicate logic. This system made it possible to define rules of inference that operate in a completely mechanical way and to write mathematics in a formal vocabulary of symbols. For example, one could use predicate logic to assert that there is a number x which is larger than y by writing $\exists xy\ (Lxy)$, which reads "There exists an x and a y such that x has the relation L (larger-than) to y."

Ludwig Wittgenstein, while a student of engineering at Manchester University in 1910, had read Bertrand Russell's 1903 *Principles of Mathematics*, which contained a summary of views about language and logic by German mathematician, logician, and philosopher Gottlob Frege at the University of Jena. In disagreement with those views, the twenty-one-year-old Wittgenstein voiced his objections in a letter to Frege, who responded by inviting the student to come to Jena and discuss logical matters. During their 1911 visit, Frege suggested that Wittgenstein transfer to Cambridge University and study with Russell, who had just published the first volume of the landmark *Principia*.

Thus in 1912—in the midst of writing volume two of *Principia*—Russell found himself searching for answers to penetrating questions from a new Viennese student. Their discussions ended in 1913 when Wittgenstein decided to leave Cambridge for Norway, where he spent a year in isolation, refining Russell's logical atomism. Later, as an enlistee in the Austrian army during World War I, Wittgenstein carried his manuscript in his soldier's rucksack. He fought on the Russian front in 1916 and the Italian front in 1918, completing *Tractatus Logico-Philosophicus* (Logical-Philosophical Treatise) while interred in a prisoner-of-war camp in Italy. Published in 1921, the slim eighty-page volume is a densely worded series of pronouncements presented like theorems, numbered in decimal notation to indicate their order within a deduction from seven axioms, the first of which is: "The world is all that is the case."

In *Tractatus* Wittgenstein presented a version of Russell's logical atomism, the picture theory of meaning: atomic propositions "picture" atomic facts because assertions "mirror" the logical structure of what they describe. For example, when a man sees an auto, he says "auto" because his reason matches the image with a word stored in his memory. Wittgenstein was also interested in the limits of language, which he equated with what can be expressed in words or other symbols. Suppose that when the man sees the auto, he feels anxious because his authoritarian father drives the same model. His malaise is not a

NASA, ESA, HEIC, AND THE HUBBLE HERITAGE TEAM (STSCI/AURA)

Some types of meta-art depict the process of viewing. Representations of the eye, whether artificially or naturally produced, can be fascinating, as exemplified by this image of the Cat's Eye Nebula from the Hubble Space Telescope. The dying star at this nebula's center has been emitting gaseous rings in 1,500-year-intervals, resulting in the concentric shells visible here.

perception of something in the world-out-there but of his inner world, arising from his gut via neural circuitry into his brain stem. His reason can't find a word that precisely matches the preverbal sensation.

According to Wittgenstein's picture theory, the facts that compose the world are mirrored by words (assertions in a language). The structure of this language gives it the power to picture a fact, but the structure itself cannot be described in the language. One can, however, create a second language—a metalanguage—with an expanded domain to describe the structure of the first. And there might be a third language capable of describing the structure of the second, and so on. But in order to conceive of the entire hierarchy of ascending languages, one must "step out" of the tower of meaning and cease speaking any of its languages.

Wittgenstein's achievement was to give a perspicacious argument that spoken language (by which he meant semantics and syntax as studied by analytic philosophy) can describe limited parts of human experience, but not intuitions about values—ethics and aesthetics—or feelings about the inner world. Some of these may be describable by less rigorous, more poetic language, while others may be truly inexpressible in words.

After World War I, Wittgenstein returned home to Vienna, where the Vienna Circle of mathematicians, logicians, and philosophers, led by Rudolf Carnap, were writing a new universal language for science. Their approach is known as logical positivism. The group read the *Tractatus*, and Wittgenstein attended a few meetings, but he was not a regular member. Carnap and his colleagues, first in Vienna and later in Chicago, tried to capture all true scientific statements in a unified description of nature. Their response to Wittgenstein's demonstration that there are limits to spoken language was to dismiss topics that lay beyond the reach of logical positivism. Meanwhile, another young Austrian in their midst, the mathematician Kurt Gödel, further undermined their goals by proving

that there are also limits to artificial language. Like Wittgenstein, Gödel was influenced by Brouwer's anti-rationalist doctrine, and according to Carnap, Gödel's proof of the incompleteness of mathematics was an expression of "the kernel of truth in the assertion made by Brouwer . . . that mathematics cannot be completely formalized." The logical positivists could find ways around Wittgenstein's *Tractatus*, but Gödel's mathematical proof could not be dismissed as a philosophical quibble.

A decade after Wittgenstein pointed out the limits of spoken language, Gödel proved a parallel result for mathematics: there are assertions that can be observed as true in a system but that cannot be deduced within that system. To describe the structure of a natural language, Wittgenstein showed that one must step outside it. Gödel demonstrated that the same is true of artificial language: in a mathematical system complex enough to describe the natural numbers, self-reference is inescapable; one must step outside the first language in order to describe the second.

Gödel devised a mechanical procedure to translate any formula written in the formal language of arithmetic—in particular, the vocabulary of *Principia Mathematica*—into a unique number, now called its "Gödel number." He then showed that the relation between the premises and conclusion of a proof could be mapped onto an arithmetical relation between the Gödel number of the string of premises, considered as a whole, and the Gödel number of the conclusion. Does a given conclusion follow from its premises? Gödel found a way to reduce the answer to the truth or falsity of an arithmetical relationship between two numbers.

Gödel's ensuing proof of the incompleteness of mathematics is as famous for its method as for its result because he translated the question of what is provable in a formal axiomatic system into what is computable in arithmetic. By achieving a dramatic result with this new style of proof, Gödel focused the attention of mathematicians on computation, pressing forward the development of computers.

Gödel's demonstration that there are true mathematical statements which cannot be deduced using only the fundamental principles of mathematics—regardless of which fundamental principles one chooses—ended a half-century of attempts to rebuild mathematics on a formal axiomatic foundation, and dealt a fatal blow to Hilbert's program. For decades, Hilbert, Russell, and many others had expended enormous effort to isolate the correct set of axioms for arithmetic and, ultimately, for all mathematics, never doubting that such a set existed. They all believed that the paradoxes that plagued fin-de-siècle axiomatic systems were introduced by imprecise thinking, never considering the possibility that these paradoxes were revealing limitations in the axiomatic approach itself. Gödel proved that there is an inherent limitation to what can be demonstrated by formal proofs and within a formal system. In particular, there can be no complete and consistent set of axioms for arithmetic. This suggests that the products of human reason can never be fully formalized and that new methods of mathematical proof and principles of demonstration forever await discovery.

Self-reference was also at the forefront of several artists' minds at the opening of the twentieth century. Two key examples of what the French call *l'art pour l'art*, usually rendered in English as "art for art's sake," or art about the nature of art, emerged at the time. The first, cubism, was a response to the quest for the foundations of art that related to nineteenth-century physiology, especially research into how the human eye and brain form a picture of the world. Pablo Picasso, Georges Braque, and Juan Gris made paintings that were imitations, but were also about imitation, featuring optical illusions and visual puns. The second example of meta-art, surrealism, was a response to criticisms of science coming from within German philosophy that were also heeded by Wittgenstein and Gödel. As mentioned above, this common influence may be why art by de Chirico, Magritte, and Escher resonates with the limits of language demonstrated by Wittgenstein and Gödel, even though there is no evidence that these artists had any direct knowledge of the mathematical writings. De Chirico, Magritte, and Escher created paintings and prints that are pictures themselves but are also about depiction, creating paradoxical art-about-art.

These artworks continue to captivate us today, and remind us that inconsistency lurks in any representational system. After 1931, when Gödel published his proof of the incompleteness theorem, mathematicians no longer imagined their science as a towering edifice resting on one axiomatic foundation, but more like an old, sprawling city with arithmetic and geometry residing in the Old Town at its ancient center. Over the centuries new neighborhoods have sprung up for algebra, calculus, and projective geometry, some separated by turf wars and others blended through intermarriage. Non-Euclidean geometry and set theory were initially viewed as outsiders but were eventually granted full citizenship. The latest arrival is a band of robotic refugees from engineering. Will these mindless machines be integrated into the daily life of mathematics?

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CHARLES BROWN

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Zoo-ology

The goals and practices of zoos are evolving as we measure their impact.

BY JONATHAN CAREY

Acres upon acres of lush evergreen vegetation sprawl across the main French botanical garden, known as the *Jardin Des Plantes,* in Paris. Much of the plant life is sculpted into winding spirals and other geometric patterns—large emerald shrubbery has been crafted by topiary experts to resemble giant birds, and an occasional flock of live flamingos can be spotted. The complex also houses four museums, focusing on everything from evolution to mineralogy. The garden has been dedicated to preserving natural history and promoting biodiversity since its establishment in the seventeenth century as a center for cultivating medicinal herbs and, soon after, as one of the world's first modern zoos.

In the early 1600s, King Louis XIII's physician, Guy de La Brosse, recognized a need for a national center to study medically useful plants. He convinced the king that such a garden should be built, and proceeded to design it himself. Originally used by La Brosse, a botanist by trade, to study and teach medicine, it opened to the public in 1640. Parisians arrived in droves to walk among the herbs and other medicinal plants. Scientists also traveled from all corners of France to study at the garden.

The new hub of floral knowledge inspired members of the French Academy of Sciences to create a similar center for fauna. They opened a national menagerie at Versailles in 1662. The menagerie housed a number of animals, its feature attraction a lone elephant gifted to King Louis XIV from the King of Portugal.

GABRIEL THOUIN

Ground plans for the Jardin des Plantes *proposed in 1820 by the gardener and architect of the gardens, Gabriel Thouin, France's most noted landscape designer at the time.*

When the French aristocracies fell to the muzzle flashes of revolution in the 1790s, the public confiscated all royal property, including the menagerie at Versailles. French botanist and writer Jacques-Henri Bernardin de Saint-Pierre, who maintained such a respect for all creatures that he believed carnivores were sinners for devouring prey alive, moved the menagerie to the *Jardin des Plantes* to provide a larger living space for the animals. In so doing, he established the world's first living history museum. The menagerie became not just a place for scientists, but a venue for all people to experience the avant garde. The public's new sense of liberty was accompanied by a childlike curiosity about previously hidden aspects of the world, including much of the natural kingdom.

Zoos today still provide a window into the exotic, although they are of course less of a novelty than during the late eighteenth century. More than 10,000 zoos are now in operation worldwide. While present-day zoos bear little resemblance to the single-cage exhibits of earlier times, the central missions of zoos not only to serve as attractions for recreation and amusement, but also to educate people and promote conservation, haven't changed.

By some measures, zoos have been successful in this endeavor. In a study released by the World Association of Zoos and Aquariums in 2014, more than 6,000 attendees at thirty zoos and aquariums around the globe filled out pre- and post-visit surveys to gauge their knowledge of how to protect biodiversity. Correct answers increased

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An adult male orangutan. In the wild, orangutans spend ninety-five percent of their time in trees.

from 69 percent pre-visit to 75 percent post-visit. A day at the zoo had apparently somewhat improved people's understanding of what should be done to preserve the natural world.

In 2007, the American Association of Zoos and Aquariums (AZA) published a similar study of twelve zoos and aquariums across the United States. Again using pre-and post-visit surveys, they found that people felt a stronger connection to nature following their visit. Attendees' belief that zoos play a premier role in education also increased.

However, some animal welfare activists have questioned these results. They note in particular the unreliability of self-report (that is, people describing their own subjective impressions) to assess the impact of zoos. These activists wonder whether zoos accomplish either of their stated goals of education and conservation.

Indeed, there is some evidence to suggest that zoos do a poor job of conserving certain species. For example, in a 2008 study published in the journal *Science*, researchers at the The Royal Society for the Prevention of Cruelty to Animals examined the lives of elephants in captivity and in the wild. They analyzed records of 786 female Asian and African elephants kept in European zoos between 1960 and 2005. They compared these captive elephants' lifespans to those of their relatives in other settings.

African elephants residing in zoos lived on average 17 years. Those elephants of the same species living at the Amboseli National Park in Kenya survived to an average age of 56. Most Asian elephants born in captivity lived to an average of 19 years old. However, their hard-working counterparts born to haul lumber throughout Burma lived to an average of 42 years. Having free space to roam—wild elephants walk on average thirty miles

a day—and engage in natural behavior like mating may enable elephants to survive longer.

Zoos also cannot adequately handle the emotional demands of elephants. These highly social creatures often live in herds of up to one hundred. Some researchers believe elephants may also succumb to post-traumatic stress disorder, especially those in captivity that lack a cohesive herd community to rely upon for support when stressful situations occur.

Fortunately, these issues have come to the attention of some regulatory bodies. The AZA has recently demanded that any facility housing only one or two elephants must add to their packs or release the elephants this year.

WARRIBEE OPEN RANGE ZOO

Kangaroos in larger, natural spaces, such as these eastern grey kangaroos at the Werribbee Open Range Zoo in Melbourne, Australia, do not show signs of stress in response to human visitors.

Like elephants, orca whales also struggle in captivity. The tanks housing them are far smaller than the vast pockets of ocean in which these animals have evolved to thrive. Aquariums are beginning to acquiesce to the demands of animal rights groups on this issue. For instance, SeaWorld in San Diego, California, announced last year that it would begin to phase out its "Killer Whale" show. They also received approval from the California Coastal Commission to expand their orca whale exhibit while ceasing to breed their eleven whales, providing more space for these large creatures.

Whether born and raised in captivity or brought into a zoo, animals seek to perform those behaviors that are innate and typical activities for them in the wild. A great deal of that activity revolves around the pursuit of sustenance—foraging or hunting. In zoos, animals are provided with food in large bunches, eliminating their need to obtain it. Eduardo Fernandez, an animal welfare researcher at the University of Washington, explained, "Most animals spend the vast majority of their time in the wild figuring out how to get food, so it's no big surprise when you put them into some type of captive setting, where you see the most problematic behavior is when they are not allowed to really exhibit the type of behaviors they normally would to get food." These abnormal activities, which serve no purpose for the individual animal or its group, can include pacing, biting, and other forms of self-mutilation, as well as species-specific stereotypies such as neck-twisting and trunk-swaying in elephants.

Besides restrictions on their natural behavior, zoo animals face another potential source of stress: the visitors.

When keepers at the Melbourne Zoo in Australia noticed some of the zoos' tiniest residents, their little penguins (*Eudyptula minor*), swimming less frequently around the visitor area than other parts of their enclosure, researcher Sally Sherwen of the University of Melbourne assembled a team to investigate whether visitors were affecting the penguin population. "The easiest way to get to the bottom of that is to compare penguin behavior with and without visitors present. So we designed an experiment that involved closing the exhibit on randomized days," explained Sherwen.

Results showed that when the viewing area was open to the public, the penguins displayed increased avoidance behavior. They pecked one another, swam less, and huddled together—an instinctive behavior penguins exhibit as a form of protection. On the days the exhibit was closed, the penguins swam more and displayed normal daily behavior. The presence of visitors had a clear negative impact on the penguins.

The plight of some captive animals begs the question of whether zoos may be undermining their own message

MIKE BLAKE/REUTERS

Bowing to public pressure, SeaWorld plans to phase out its "Killer Whale" shows this year and provide more space for their captive orcas.

about conservation. Acknowledging this problem, many institutions are searching for ways to provide their animals with a more naturalistic lifestyle. For example, instead of simply giving giraffes a large portion of food all at once, some zoos have implemented hanging pouches filled with a hay-like substance that allow giraffes to graze the entire day. Susan Friedman, a psychology professor at Utah State University who applies behavior analysis to improve the lives of captive animals, has suggested other possibilities, including the creation of a private area where animals can go when they want to avoid humans, or the use of technology to allow animals to better engage their environment as in the wild.

Some zoos are also exploring ways to make the animals less aware of their human voyeurs. At the Chester Zoo in England, researchers from Durham University introduced tropical shrubs between the glass enclosure and the visitors. They found that this visual and spatial barrier reduced the stress response of the zoo's mandrill monkey population. When the shrubs were not present and visitors approached the glass, the mandrills would frequently pace or display their teeth—an adversarial expression, sometimes mistaken for a smile, that is known as a fear grimace. The shrubs increased the distance between visitors and the enclosure by one meter, which was enough to decrease the mandrills' pacing and fear grimacing by 54 percent. The monkeys also showed increases in climbing, eating, and other natural behaviors, which are not only beneficial for the animals, but help to provide visitors with a more authentic experience of primates in the wild.

Along with how animals are housed, some zoos have taken creative steps to improve their educational model. In 2006, the New England Aquarium introduced several features to their penguin exhibit, including an underwater camera, a station to listen to penguin calls, and, most creatively, a periscope that allowed visitors to shine a light on the bottom of the pool. The penguins would then dive in the pool and follow the light as if hunting a fish. This enabled visitors to observe the distinct swim patterns of a penguin from above, while permitting the animals—which can spend up to five months in a row in the water—to engage in their fundamental behavior without disturbance from humans nearby.

PIXELBAY

Captive giraffes may benefit from grazing throughout the day, as they do in the wild, rather than receiving all their food once daily.

Animal welfare researcher Eduardo Fernandez suggests an even more practical and inexpensive method for zoo visitors to learn about and engage with animals: live feedings in which visitors bring their own food. This type of live feeding has a checkered past: in earlier days, people attending zoos and circuses would bring any type of snack for the animals, often consisting of unhealthy and unfit choices. Zoos can avoid this issue by providing strict guidelines regarding what foods to bring, along with information about how specific foods affect each animal. In this way the public could learn about what animals enjoy eating, how they eat, and the physiological effects that food has on different animals' bodies.

Other zoos have made an effort to focus on animals they can amply provide for, while still teaching the fundamental principles of biodiversity. The Detroit Zoo, for example, recently developed a snail exhibit. While not as flashy as lions and tigers, these slimy invertebrates serve a valuable purpose. According to Mark Bekoff, a former professor of ecology and evolutionary biology at the University of Colorado, "If you want to educate on basic

MARY SCHWALM/AP

As one form of enrichment, the Roger Williams Park Zoo in Providence, Rhode Island, provides anteaters with objects from which they must use their tongue to extract food bits.

principles of behavior, evolution, ecology, then snails are great. I love the example of the Detroit Zoo saying that they can't do certain things they would like to do, but they need to do better by the animals." Bekoff noted that if zoos want to promote conservation and education, then being realistic about which animals can and cannot survive in captivity should be their first responsibility.

Along with species that are better suited to live in smaller spaces, zoos could place more emphasis on housing species that do not suffer from visitor interactions. Sherwen and her team have also investigated how meerkats and kangaroos respond to humans in zoos. Their results with these species are encouraging.

At two Australian zoos, one in Melbourne and the other in Meribee, researchers posted signs on some days around the meerkat exhibits advising visitors to be as quiet as possible and not interact with the animals. The researchers stood near the exhibit in zoo uniforms, as though to enforce the request. On other days, no signs were posted and the researchers wore plain clothes during their observations. They recorded the intensity of visitors' animal-directed behavior, as well as noise level. They further noted how close the animals stayed to the visitor viewing area, and recorded an array of both vigilant and typical behaviors. They found that the signage did reduce crowd noise and the intensity of visitor behavior at all the exhibits. However, meerkat behavior did not change between conditions. In other words, meerkats showed no outward response to heightened levels of visitor activity. It seems that meerkats can adapt to the presence of humans, and may be a suitable zoo species.

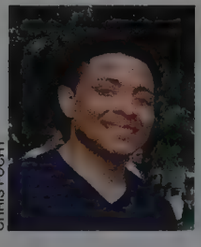
MARY SCHWALM/AP

To engage snow leopards in retrieving their food, the Roger Williams Park Zoo places meatballs inside cardboard boxes.

Sherwen and her colleagues also examined how visitor numbers impacted activity and stress levels in kangaroos housed in free-range enclosures, large areas where people can walk through the exhibit with no barriers between them and the animals. While increasing visitor numbers did correspond to increased vigilance from the kangaroos, it did not affect the distance kangaroos kept from the visitor pathway. Moreover, concentration of a stress-related metabolite in the kangaroos' feces did not vary with visitor numbers. As with meerkats, kangaroos in these broad enclosures did not seem to be negatively impacted by the presence of humans.

Thus it appears that some species may take better to zoo life than others. Further studies exploring how various species fare in the presence of humans and in captive environments can help zoos and aquariums select the most appropriate animals for their exhibits.

Just as Jacques-Henri Bernardin de Saint-Pierre moved the royal menagerie to the *Jardin des Plantes* to better accommodate the animals, zoo directors may continually change their idea of how animals should live in captivity with the more knowledge they acquire. As additional sanctuaries and national parks open with vast stretches of rolling pastures, and as zoos begin to limit their large animal populations, another shift could be on the horizon.



CHRIS FOCHT

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Perspective

The Routes Not Taken

If the *Beagle* had sailed a different course, what would Darwin have seen and how might that have shaped his thinking?

BY JONATHAN B. LOSOS

During Charles Darwin's journey on the *Beagle*, two aspects of what he saw were particularly influential. First was the phenomenon of geographic variation. The then-vice-governor of the Galápagos, Mr. Lawson (born Nicolai Olaus Lossius in Norway), told Darwin that he could tell what island a tortoise was from by looking at its shell. This surprised Darwin—why should tortoises vary from one island to another? Then he noticed the same thing when he started looking at mockingbirds, which also differed among the islands. These observations led Darwin to question the idea that species were immutable, produced in their present form by a creator. Maybe they could change, evolve.

The second key feature of the Galápagos concerned its common land birds. Darwin collected a number of these mostly seed- and fruit-eating species, and thought that the big-beaked bird was a grosbeak, the small one with a slender beak was a warbler, and the others were common finches. Consequently, he paid the birds little attention, considering them the local representatives of families that are found in Europe and elsewhere.

When the *Beagle* arrived back in England, Darwin turned his collections over to specialists. The birds went to John Gould, the most noted ornithologist of the time. After studying the specimens for several weeks, Gould reported back to Darwin that he was wrong: the birds were not members of different families that occurred in Europe. Rather, they were all

members of a single family—a family of birds hitherto unknown to science that apparently only occurred in the Galápagos. He gave them the taxonomic name Geospizinae, and we now call them "Darwin's finches."

Darwin quickly realized the significance of this discovery. As he wrote in the second edition of his travelogue, *Voyage of the Beagle*, in 1845, "Seeing this gradation and diversity of structure in one small, intimately related group of birds, one might really fancy that from an original paucity of birds in this archipelago, one species has been taken and modified for different ends."

The wording may have been coy, but the meaning was clear: species evolve, diverging into multiple descendants and adapting to different circumstances. It took him another twenty years to fully develop his ideas about the mechanism of this evolution, natural selection, but it's clear that his observations on the Galápagos and the evidence he uncovered there were instrumental in shaping his ideas.

Hawaiian honeycreepers, exhibiting a wide array of specialized beaks, all evolved from a common finch ancestor.

THE HAWAIIAN HONEYCREEPERS: DREPANIDINAE BY H. DOUGLAS PRATT (OXFORD UNIVERSITY PRESS, 2005) USED BY PERMISSION. COPYRIGHT © 2005 BY H. DOUGLAS PRATT.

But what if Darwin never visited the Galápagos? Suppose the British Admiralty's orders to the *Beagle's* captain, Robert FitzRoy, were not "to proceed with all convenient expedition, successively to Madeira or Teneriffe; the Cape de Verd Islands; Fernando Noronha," but rather to go somewhere else—say, the Caribbean Sea? What would Darwin have seen there, and how would it have affected his thinking?

In the Caribbean he would have seen lizards, and lots of them, particularly those in the genus *Anolis*. Darwin was a great naturalist, a keen observer. He

Cuvier's anole (Anolis Cuvieri) is a crown giant that occupies the canopy of trees on Puerto Rico.

JONATHAN B. LOSOS

Although trunk crown anoles are known on Cuba (left)*, Jamaica* (middle)*, Puerto Rico* (right)*, and Hispaniola* (bottom)*, they are distant relatives genetically. They have evolved independently to occupy the same ecological niche on each island.*

would have noted these lizards, and studied their differences. Although Darwin saw some fantastic lizards in the Galápagos, their unattractive appearance forced his attention elsewhere. Referring to the marine iguana, the only sea-going modern-day lizard, now famous for eating seaweed underwater and blowing the excess salt out of special glands in its nostrils, he wrote in the *Voyage*, "It is a hideous-looking creature of a dirty black color, stupid and sluggish in its movements." And of its golden-yellow cousin, the five-foot-long, cactus-munching land iguana, Darwin noted, "They are ugly animals. From their low facial angle, they have a singularly stupid appearance."

He might have taken more favorably to the beautiful, sleek, and energetic anoles of the Caribbean. Certainly, he could not have failed to see them, given their extraordinary abundance. He would have discovered that many species occur on each of the islands of the Greater Antilles (Cuba, Hispaniola, Jamaica, and Puerto Rico). The species live in different habitats and have different anatomical features that are adaptations to the part of the habitat they occupy. Strikingly, if you go from one island to the next, you see the same set of habitat specialists on each island.

On Cuba, one species lives on tree trunks near the ground and has long legs for running quickly and jumping far to capture prey and confront territory intruders on the ground. A verdant green species occurs up in the canopy. Its large, sticky toepads help it move on slick leaves. Another green species lives high in the canopy, but is much larger; the giant of the anole world, its massive head enables it to gulp down other anoles and even baby birds. A fourth species patrols narrow twigs on the trees' periphery, with very short legs that are well-suited for moving on narrow and irregular surfaces. Yet another species lives amidst the grass, its slender body able to maneuver between grass blades, with a tail as much as four times the length of its body.

If Darwin visited the other Greater Antillean islands, he would have seen the same set of habitat specialists as on Cuba (except no grass-dweller in Jamaica). All three islands have trunk-ground, leaf-canopy, canopy giant, and twig specialists very similar to the Cuban species.

Darwin wouldn't have known it (nor, probably, the specialists back in England), but this suite of specialists evolved independently on each island. Modern-day examination of DNA indicates that, for example, the twig anoles on the different islands are not closely related to each other—they've evolved their twiggy adaptations independently, an example of convergent evolution. What is unusual about the anoles is that the entire community is convergent: the same set of habitat specialists has evolved on each island.

Caribbean anoles have an important parallel with Darwin's finches. Both are examples of what is called "adaptive radiation," the phenomenon in which an ancestral species gives rise to a variety of descendants, each adapted to occupy a different ecological niche, using a different part of the environment or eating different foods.

And just as Darwin was influenced by the adaptive radiation of Galápagos finches, he would have been impressed by Caribbean anoles; indeed, he wouldn't even have needed James Gould to realize that the "gradation and diversity of structure" in anole habitat specialists were all variations on the same theme, the result of divergence from a common ancestor. Moreover, just as with the Galápagos mockingbirds and tortoises, he would have noticed the

JONATHAN B. LOSOS

differences among the twig anole species from one island to another (and among members of each of the other habitat specialist types). In sum, had Darwin been sent to the Caribbean instead of the southern continents, he would have observed very much the same phenomena and most likely been led to the same conclusions. Had Darwin been sent to the Caribbean, *The Voyage of the Beagle* account of what he saw may have been quite different, but *On the Origin of Species* would have been very much the same.

How robust is this counterfactual conclusion? Suppose instead of going to the Galápagos or the Caribbean, the *Beagle* had sailed to Hawaii. There, Darwin would have seen the amazingly diverse honeycreepers—all the descendants of a single species of finch—with their extraordinarily variable beaks adapted to using different food sources: very long curved beaks for sipping nectar, big beaks for crushing seeds or eating fruits, and little beaks for picking out insects. The significance of these beak differences among honeycreepers would not have escaped Darwin. He would have noted other adaptive radiations as well, such as the silversword and lobelia plants.

What would Darwin have seen if, instead of sailing just south of Madagascar, the *Beagle* had stopped there for a visit? In a word: lemurs. Ring-tailed, brown, ruffed, fat-tailed, and mouse lemurs, as well as the incomparable aye-aye. Those are only the smaller members of the lemur radiation, the ones that survived the onslaught that unfolded when humans arrived on the island. Darwin made important paleontological discoveries in Argentina, and might have done the same in Madagascar, finding remains of *Palaeopropithecus*, a 75-pound lemur that hung upside down like a tree sloth, using long curved arms and digits to suspend itself. Or *Megaladapis*, an animal whose proportions were very similar to a koala, but probably weighing in at about one hundred pounds. Or *Archaeoindris*, a terrestrial lemur the size of a gorilla.

Even aside from the lemurs, Madagascar could be called the island of adaptive radiations: vangas (a group of birds as diverse in beak form as the Hawaiian honeycreepers), tenrecs, chameleons, geckos, and many other animals and plants all exhibit the same phenomenon of diversification.

So the *Beagle's* itinerary almost didn't matter. Any large, isolated island probably would have revealed examples of adaptive radiation. Darwin would have noted the diversity and likely would have been moved in the same intellectual direction.

Adaptive radiation is a phenomenon most clearly seen on islands. Oceanic islands—those that were never connected to a mainland, but emerged out of the sea by volcanic action—are populated by species that can make their way across the intervening ocean. Not all species are capable of such expeditions; frogs and trees are particularly

MELISSA LOSOS

Examples of the diverse lemurs found on Madagascar: clockwise from above, the indri, Coquerel's sifaka, Milne-Edwards' sportive, fat-tailed dwarf, and brown lemur

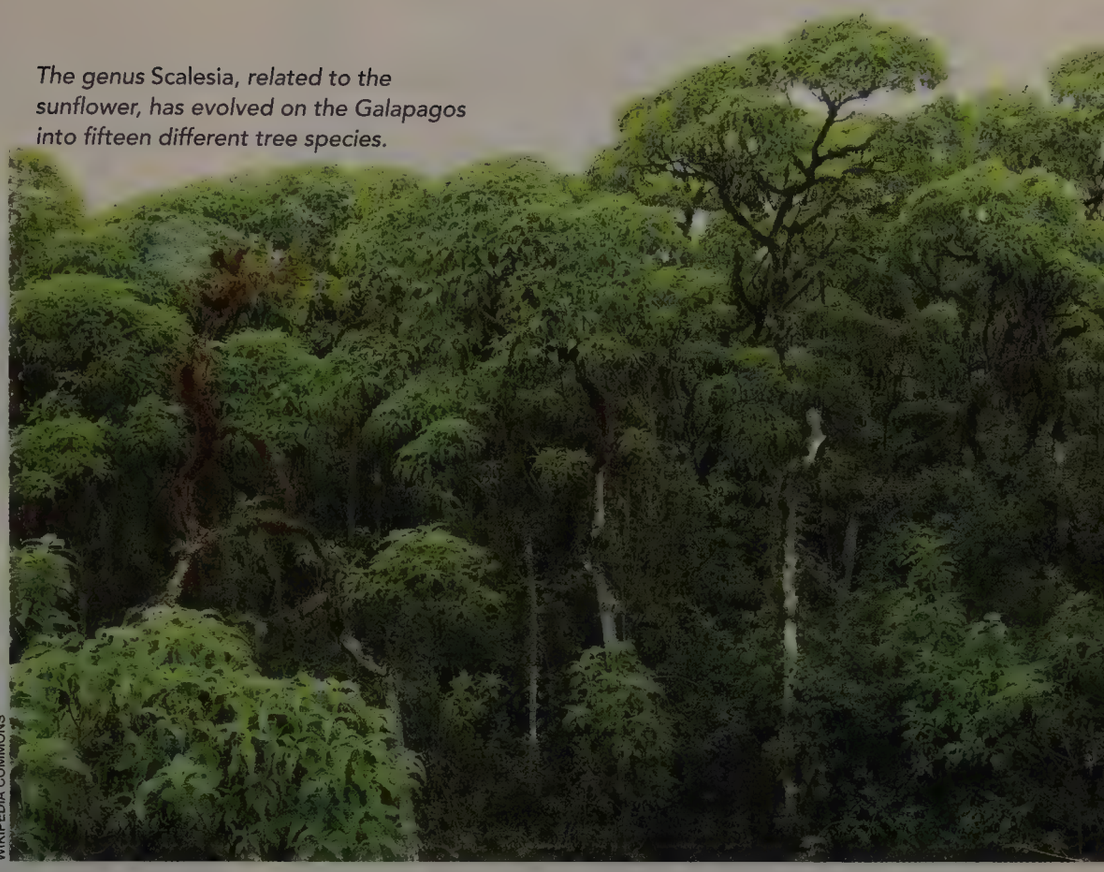
ill-equipped, whereas flying animals generally fare much better. And chance plays a role: a tortoise might reach one island and not another.

On islands, many resources are underutilized because the species that normally use them on the mainland have not successfully colonized the island. A finch on the mainland may not be able to sustain itself sipping nectar because other species are already much better adapted for the task. However, if a finch finds its way to an island where there are no hummingbirds or other nectar specialists, that finch species can start using the nectar and over time develop adaptations to specialize on it. This "ecological opportunity," the result of the varying colonization success of different species, is what sets the stage for adaptive radiation and explains why it so often occurs on islands.

No better example of ecological opportunity exists than island trees. Most trees are very poor overwater dispersers—their large seeds have difficulty surviving long oceanic voyages (though the coconut, the palm tree's seed, is an exception), and they're too big to be carried on the feet or in the guts of birds. As a result, almost no mainland trees, other than palms, get to islands. Consequently, there's an ecological opportunity for any weed or small bush lucky enough to get to an island. In the absence of large trees, any plant that is a little bit taller than its neighbors and able to soak up all the sun's rays will have an advantage. Many types of plants that are herbaceous shrubs or bushes on the mainland have evolved into trees on islands. On Saint Helena in the South Atlantic, the cabbage tree comes from a plant family that normally grows near the ground. In the Galápagos, there's an entire adaptive radiation of *Scalesia* trees, related to the sunflower.

Yet, ecological opportunity doesn't explain everything

about island evolution. About three hundred and fifty miles off the Costa Rican coast in the Pacific Ocean, Cocos Island is biologically rich, blanketed in rainforest. Of particular interest is the Cocos Island finch, a small, nondescript, warbler-like bird. What makes this species a celebrity to evolutionary biologists is its heritage. It is a member of the Darwin's finch family, the only one not found in the Galápagos, which lie five hundred miles to the south. If these finches diversified so wildly in the Galápagos, why not also in the tropical cornucopia that is Cocos? A number of possibilities come to mind.



The genus Scalesia, *related to the sunflower, has evolved on the Galapagos into fifteen different tree species.*

WIKIPEDIA COMMONS

Perhaps they haven't been there long enough—but DNA analyses suggest that the birds arrived from the Galápagos long ago, sufficient time for diversification to occur.

Perhaps ecological opportunity doesn't exist or other birds got there first and usurped the resources. This hypothesis is also unlikely, given the richness of the island and the lack of radiation of other bird groups. Moreover, the Cocos Island finch is extraordinarily varied in diet, much more so than other birds, suggesting that ecological opportunity does exist, and that the finches have taken advantage of it through behavioral variability.

Perhaps the species doesn't have the genetic capability to adapt to the resources available—but given that the species is a member of the Darwin's finch clan, this explanation does not seem viable.

Or perhaps, for some reason, the species has been unable to split into multiple species. Adaptive radiation requires not only adaptation to different niches, but also the sundering of one species into many. If speciation doesn't occur, then adaptive radiation will be forestalled. Traditionally, evolutionary biologists have thought that populations need to be geographically separated before they can evolve into different species. To the extent that this is true—and this point is currently hotly disputed—then an isolated island setting that prevents population fragmentation may preclude speciation and, consequently, adaptive radiation. By contrast, the Galápagos finches occurred in an archipelago consisting of several islands, where populations could become isolated, speciate, and then re-colonize. To me, a roadblock to speciation seems the most likely explanation for lack of adaptive radiation in the Cocos finch.

The Cocos finch is not alone in failing to diversify in the face of ecological opportunity. Indeed, speciation is almost unheard-of in birds on isolated islands smaller than Madagascar. A similar phenomenon occurs in *Anolis* lizards, where speciation is restricted to the large islands of the Greater Antilles and hasn't occurred on the smaller, yet resource-rich, islands of the Lesser Antilles. Studying the interplay between speciation dynamics and ecological opportunity is an important current direction in island evolution research.

Counterfactually, then, not all potential sailing routes would necessarily have led Darwin to his evolutionary insights. Had the *Beagle* been sent only to remote, small islands, it's possible that he would not have made the key observations that played such an important role in his thinking (although snails and beetles can radiate on much smaller islands than vertebrates can). What would have happened in that case? Would the other main lines of evidence that Darwin accumulated have been enough to lead him to the same conclusions? Quite possibly, given Darwin's analytical thinking. We do know, however, that what he discovered on the route that was taken has made a huge difference.

Jonathan B. Losos is the Monique and Philip Lehner Professor for the Study of Latin America, as well as a Professor of Organismic and Evolutionary Biology, at Harvard University. He is also Curator in Herpetology, Harvard Museum of Comparative Zoology. He can be reached at jlosos@oeb.harvard.edu, and he can be seen on the Howard Hughes Medical Institute short film, *The Origin of Species: Lizards in an Evolutionary Tree,* available at http://www.hhmi.org/biointeractive/origin-species-lizards-evolutionary-tree.

Around the Country

Marine Life Up Close

On Saturday, November 21, 2015, the new *Marine Life* exhibition in the Putnam Family Gallery opened at the Harvard Museum of Natural History. The centerpiece of the new exhibition—a floor to ceiling re-creation of life in New England's coastal waters—immerses visitors in the astounding diversity and dynamic interplay among animals in marine communities just off local shores. As models of glowing jellies, a giant sea turtle, and other sea animals appear to swim above their heads, museum visitors will learn about new research and explore displays of real fishes, mollusks, crustaceans, corals, and other marine organisms selected from the world-renowned collections of Harvard's Museum of Comparative Zoology. A special interactive display introduces visitors of all ages to the amazing world of jellyfish, and the ocean exploration theater takes viewers on a multimedia journey of discovery into the surface and deep oceans of the world, guided by Harvard biologists.

The amazingly realistic dioramas were created by Terry Chase of the Chase Studio in Missouri. Long considered the leader in the field of museum exhibit arts, Chase Studio has designed and built thousands of natural history exhibits for over 250 museums and nature centers.

This lifelike re-creation of a finned fish is part of the stunning diorama on display in the new *Marine Life* exhibition.

Harvard Museum of Natural History
26 Oxford Street, Cambridge, Massachusetts
617-495-3045 • www.hmnh.harvard.edu

ARIZONA

Phoenix

ARIZONA SCIENCE CENTER
Ongoing: **"My Digital World."** This gallery introduces visitors to the science behind digital communications, how they work, and how they are utilized to create and share ideas and information.
600 East Washington Street
602-716-2000
www.azscience.org

CALIFORNIA

Los Angeles

CALIFORNIA SCIENCE CENTER
Ongoing: **"Journey to Space: The Exhibition."** Examine the challenges and innovative solutions required for human space exploration, including the very real dangers astronauts face during their missions high above the Earth. Get a feeling for what space is like, how we are learning to live and work in space, and how we are preparing for bolder and more distant missions.
Exposition Park
700 Exposition Boulevard
323-SCIENCE (323-724-3623)
www.californiasciencecenter.org

NATURAL HISTORY MUSEUM OF LOS ANGELES COUNTY
Ongoing: **"Visible Vault: Archaeological Treasures From Ancient Latin America."** In this unique permanent exhibition, more than 600 fascinating artifacts and treasures from ancient America are on view, illustrating the sophistication and diversity of the civilizations that thrived throughout the Americas prior to European exploration.
Exposition Park
900 Exposition Boulevard
213-763-DINO
www.nhm.org

San Diego

SAN DIEGO NATURAL HISTORY MUSEUM
Opening March 19: **"Whales: Giants of the Deep."** This exhibition's unique blend of science, storytelling, and innovative interactive displays gives visitors the opportunity to discover more about whales, which are some of the world's most elusive creatures. Developed and presented by the Museum of New Zealand Te Papa Tongarewa, the exhibition features two fully-articulated sperm whale skeletons, and showcases amazing and rare specimens from Te Papa's whale collection, one of the largest in the world.
Balboa Park
1788 El Prado
619-232-3821
www.sdnhm.org

COLORADO

Denver

DENVER MUSEUM OF NATURE AND SCIENCE
Opening February 12: **"Chocolate: The Exhibi-**

tion." Chocolate. The word conjures up visions of candy bars, hot fudge sundaes, and rich brownies, yet its rustic origins extend back thousands of years. In this new exhibition, trace the story of the "food of the gods," from its earliest cultivation among the ancient peoples of the rain forest to its status today as the world's favorite sweet. Immersive exhibits, fun interactives, and detailed replicas and objects place chocolate under the lenses of science, history, and popular culture.
2001 Colorado Boulevard
303-370-6000
www.dmns.org

CONNECTICUT

New Haven

PEABODY MUSEUM OF NATURAL HISTORY
Ongoing: **"Hall of Minerals, Earth, and Space."** This permanent exhibition is designed to foster an appreciation for the wonders of our planet and solar system. Visitors are introduced to the processes that shape the earth—earthquakes, volcanic eruptions, and collisions with meteors—and to global changes in the continents, oceans, and atmosphere throughout geologic time.
Yale University
170 Whitney Avenue
203-432-5050
www.peabody.yale.edu

DELAWARE

Wilmington

DELAWARE MUSEUM OF NATURAL HISTORY
Ongoing: **"Nature Nook."** The interactive Nature Nook is a place where young children can explore animal habitats while having fun. Step inside a cave, walk through a woodland, enter an eagle's nest, and lots more!
4840 Kennett Pike
302-658-9111
www.delmnh.org

FLORIDA

Gainesville

FLORIDA MUSEUM OF NATURAL HISTORY
Ongoing: **"Our Energy Future."** Explore the museum's newest permanent exhibition. It is full of tips about reducing energy use at home, and features hands-on activities. Learn about alternative energy sources, the rooftop solar array that powers part of the museum, and more.
University of Florida,
Cultural Plaza
SW 34th Street and Hull Road
352-846-2000
www.flmnh.ufl.edu

GEORGIA

Atlanta

FERNBANK MUSEUM OF NATURAL HISTORY
Opening February 6: **"Wild Music."** Whales compose, bullfrogs chorus, songbirds greet the dawn, and people everywhere sing and dance. Music is all around us, produced by creatures large and small. Explore sound and music in nature and in life through whimsical, hands-on activities.
767 Clifton Road NE
404-929-6300
www.fernbankmuseum.org

HAWAII

Honolulu

BISHOP MUSEUM
Through February 28: **"Duke Paoa Kahanamoku."** This exhibition brings the many facets of Duke Kahanamoku to life by enlivening the J. M. Long Gallery with graphics, photographs, cultural artifacts, video clips, and interactive media displays.
1525 Bernice Street
808-847-3511
www.bishopmuseum.org

IDAHO

Idaho Falls

MUSEUM OF IDAHO
Ongoing: **"Race For Atomic Power."** Learn about the dramatic scientific and political adventure that occurred in Idaho's own backyard—including information about the first usable amounts of electricity produced by a nuclear reactor, the first city to be powered by nuclear energy, the birth of the nuclear navy, and many other important advances in nuclear power.
200 North Eastern Avenue
208-522-1400
www.museumofidaho.org

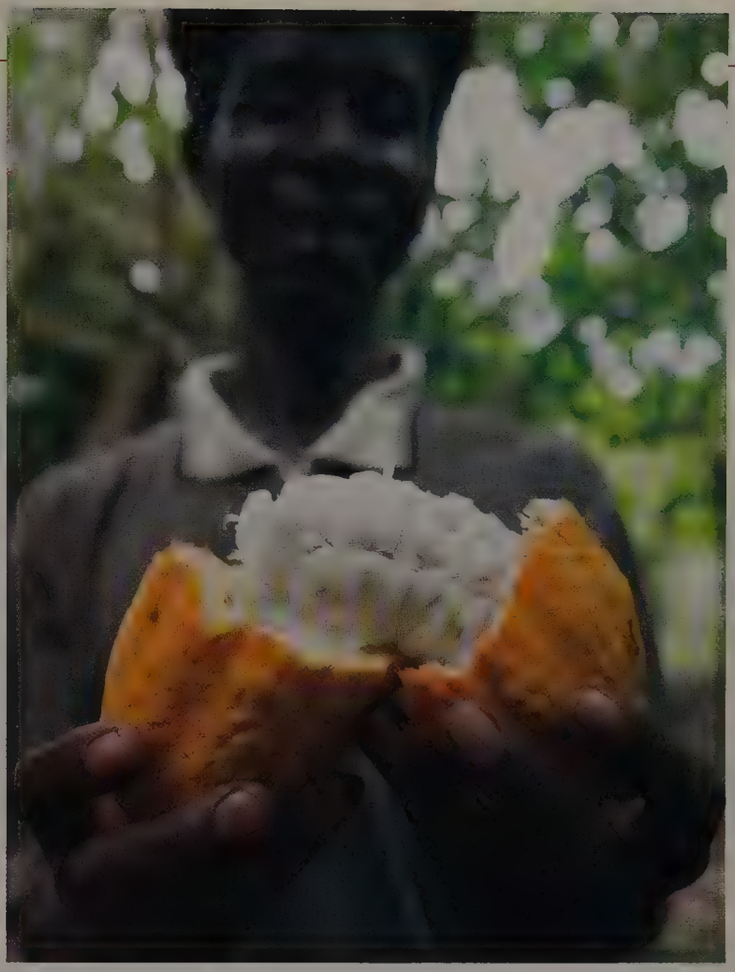


IMAGE USED WITH PERMISSION OF CARGILL COCOA & CHOCOLATE, INCORPORATED

This man is holding an opened cacao pod, the dried seeds of which are used in making cocoa, chocolate, and cocoa butter. Learn more about how the world's favorite sweet is made in "Chocolate: The Exhibition," opening February 12 at the Denver Museum of Nature and Science.

MEMBERSHIP HAS ITS REWARDS

Institutions marked with participate in the Passport program run by the Association of Science-Technology Centers (ASTC). If you're a member of a participating museum or science center, you may receive free admission at nearly 350 other museums and science centers around the world.

See www.astc.org/passport for more information.

Children play on the spider's web, a popular attraction at "Wild Walk," now open at The Wild Center, Natural History Museum of the Adirondacks.

ILLINOIS

Chicago

THE FIELD MUSEUM

Through April 10: **"The Greeks: Agamemnon to Alexander the Great."** Explore epic stories from the perspectives of the ancient Greeks themselves, including men and women known to us through historical accounts, mythological tales, and the archaeological record. More than 500 artifacts from ancient Greece are on display.

1400 South Lake Shore Drive
312-922-9410
www.fieldmuseum.org

MINNESOTA

Minneapolis

BELL MUSEUM OF NATURAL HISTORY

Ongoing: **"Under the Fig Leaf: Rainforest Research."** In this permanent exhibition, explore the rainforest and learn about rainforest-related research being done by Bell scientists.

University of Minnesota
10 Church Street, SE
612-624-7083
www.bellmuseum.umn.edu

MISSOURI

Saint Louis

SAINT LOUIS SCIENCE CENTER

Ongoing: **"Experience Energy."** Learn about the different forms that energy can take, see how energy becomes electricity, and learn why energy efficiency makes a difference. The Experience Energy gallery also presents alternate methods of electrical generation and ideas to conserve energy.

5050 Oakland Avenue
800-456-SLSC
www.slsc.org

NEW MEXICO

Albuquerque

NEW MEXICO MUSEUM OF NATURAL HISTORY AND SCIENCE

Ongoing: **"The Hall of the Stars."** This permanent exhibition helps to explain how the night sky is organized. Rather than just showing the sky visible on any given night of the year, the Hall of the Stars allows visitors to see all of the year's stars and constellations in the same way that a world map allows us to visualize the whole globe.

1801 Mountain Road NW
505-841-2800
www.nmnaturalhistory.org

NEW YORK

New York

AMERICAN MUSEUM OF NATURAL HISTORY

Through August 14: **"The Secret World Inside You."** Our bodies are home to approximately 100 trillion bacteria living inside us and on us—a vast community known as the microbiome. This exhibition explores the rapidly evolving science that is revealing the complexities of the human microbiome and reshaping our ideas about human health, offering new perspectives on common health problems including allergies, asthma, and obesity.

Central Park West at 79th Street
212-769-5100
www.amnh.org

Tupper Lake

THE WILD CENTER, NATURAL HISTORY MUSEUM OF THE ADIRONDACKS

Ongoing: **"Wild Walk."** A trail of bridges leads high above the Adirondack forest where visitors can walk over the tree tops and explore the stunning natural environment from a new perspective. The recently-opened Wild Walk includes a four-story twig tree house, swinging bridges, a spider's web where guests can play, and an oversized bald eagle's nest at the highest point where visitors can perch and imagine life as one of the raptors.

45 Museum Drive
518-359-7800
www.wildcenter.org

NORTH CAROLINA

Durham

MUSEUM OF LIFE AND SCIENCE

Ongoing: **"Hideaway Woods."** This new nature playspace is a two-acre, forested learning environment featuring treehouses, a flowing streambed, and fanciful nature sculptures. Connected by rope bridges, the treehouse village encourages you to flex your body and imagination all while viewing the world around you from a new perspective.

433 West Murray Avenue
919-220-5429
www.ncmls.org

Raleigh

NORTH CAROLINA MUSEUM OF NATURAL SCIENCES

Through March 27:

"Extreme Mammals." This eye-opening exhibition explores the diversity of the biggest, smallest, and most amazing mammals that have ever roamed the Earth.
11 West Jones Street
919-707-9800
www.naturalsciences.org

OREGON
Eugene
MUSEUM OF NATURAL AND CULTURAL HISTORY
Ongoing: **"Site Seeing: Snapshots of Historical Archaeology in Oregon."** From a nineteenth-century working-class family in Portland to a Chinese mining community in Jacksonville, this exhibition tells the stories of five historical sites recently excavated by museum archaeologists.
1680 East 15th Avenue
541-346-3024
natural-history.uoregon.edu

PENNSYLVANIA
Philadelphia
THE ACADEMY OF NATURAL SCIENCES OF DREXEL UNIVERSITY
Through May 30: **"Tarantulas: Alive and Up Close."** Tarantulas have a reputation that precedes them—terrifying, fast, hairy, scary—the biggest, baddest, and most fearsome of all spiders. In this new hands-on exhibition, visitors come face-to-face with a stunning array of live tarantulas—fangs and all. Get the facts on why tarantulas are so hairy as you venture through an air current that simulates the sensitivities of a hairy spider. Explore a tarantula burrow and get your picture taken with these live eight-legged beasts!
1900 Benjamin Franklin Parkway
215-299-1000
www.ansp.org

TEXAS
Houston
HOUSTON MUSEUM OF NATURAL SCIENCE
Through September 5: **"La Virgen de Guadalupe: Empress of the Americas."** She's been a symbol of hope, protection, and comfort to her followers for almost 500 years, but why? What is it about her that has inspired millions throughout the Americas? Today, her image represents not only a great miracle, but the identity of a nation of believers. Trace the story back to its origins in this new exhibition.
5555 Hermann Park Drive
713-639-4629
www.hmns.org

UTAH
Salt Lake City
NATURAL HISTORY MUSEUM OF UTAH
Through May 1: **"Geckos."** Geckos are incredibly adaptable and have conquered habitats from balmy tropical beaches and lush rainforests to frigid mountain slopes and parched deserts. More than 1,200 species range from shadowy, nighttime hunters with bulging eyes and squawking voices to bold nectar-eaters that scamper around in daylight, adorned in neon colors. Come meet live geckos from around the world, and explore interactives that allow you to experience gecko night vision, listen to gecko voices, and try to spot camouflaged geckos.
301 Wakara Way
801-581-6927
nhmu.utah.edu

WASHINGTON
Seattle
PACIFIC SCIENCE CENTER
Through May 1: **"Math Moves!"** This exhibition uses a variety of hands-on activities to make experimenting with concepts at the heart of math memorable and fun.
200 Second Avenue North
206-443-2001
www.pacsci.org

WISCONSIN
Milwaukee
MILWAUKEE PUBLIC MUSEUM
Ongoing: **"Crossroads of Civilization."** This permanent exhibition explores how the ancient civilizations of Africa, Europe, and Asia came together to form an epicenter of complex culture, creating not just a physical crossroads, but an intellectual one as well. The exhibition brings the ancient world to life by presenting over 200 artifacts from the museum's collections.
800 West Wells Street
414-278-2702
www.mpm.edu

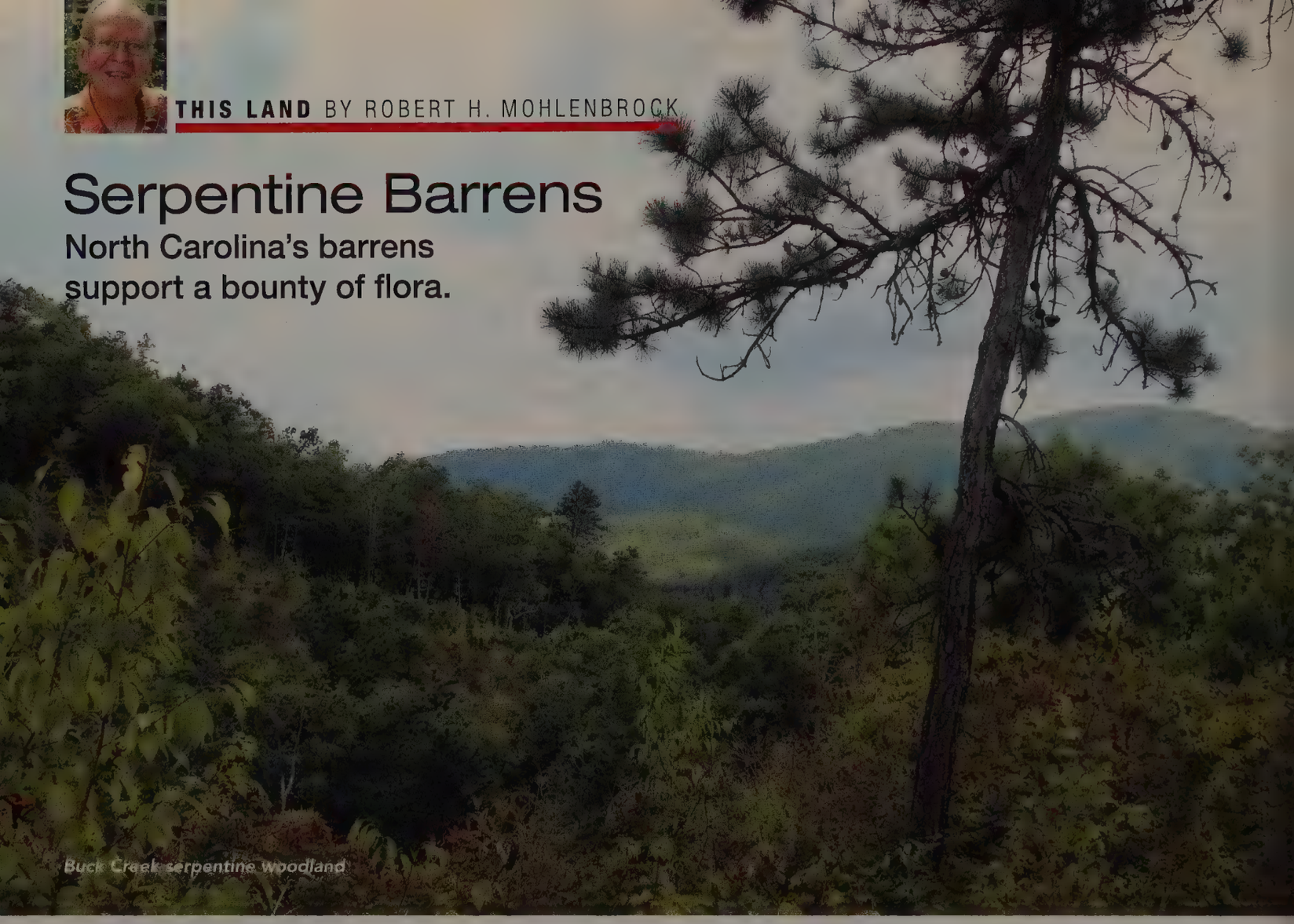
This Mexican red knee tarantula is just one of the many live species on display in the exhibition "Tarantulas: Alive and Up Close," now open at The Academy of Natural Sciences of Drexel University in Philadelphia.

THE WILD CENTER; OUTHOUSE EXHIBIT SERVICES

THIS LAND BY ROBERT H. MOHLENBROCK

Serpentine Barrens

North Carolina's barrens support a bounty of flora.



Buck Creek serpentine woodland

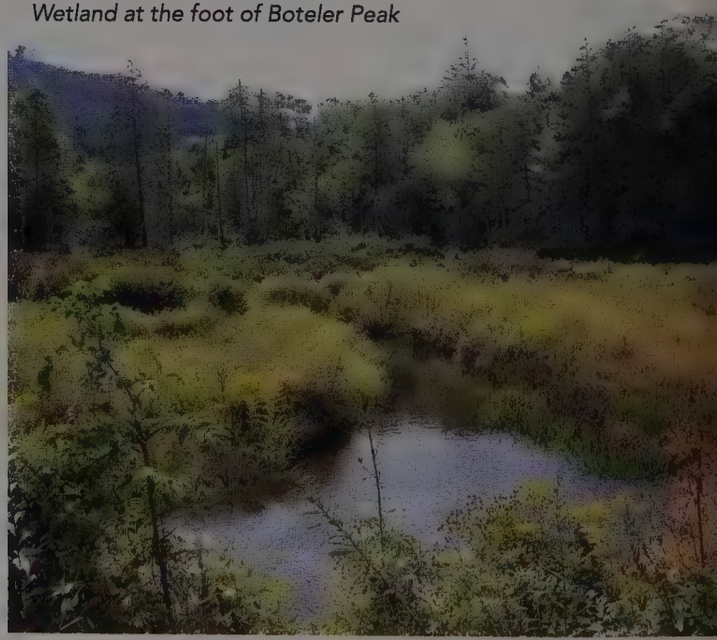
DANA KOOGLER

Nantahala National Forest, located in the southwestern corner of North Carolina, is one of five national forests in the beautiful southern Appalachian Mountains, and is among the prettiest in the country. Lying between the southern edge of the Great Smoky Mountains National Park and the state of Georgia, this national forest of more than 530,000 acres consists of heavily wooded mountains, deep, rocky gorges, clear and fast-moving rivers and streams, and many sparkling waterfalls. The Nantahala River nearly bisects the forest where it has carved the spectacular nine-mile-long Nantahala Gorge. According to the Nantahala National Forest website, "Nantahala is a Cherokee word meaning 'land of the noon day sun,' a fitting name for the Nantahala Gorge, where the sun only reaches to the valley floor at midday." Cullasaja Gorge and Tuckasegee Gorge are other spectacular gorges in the national forest.

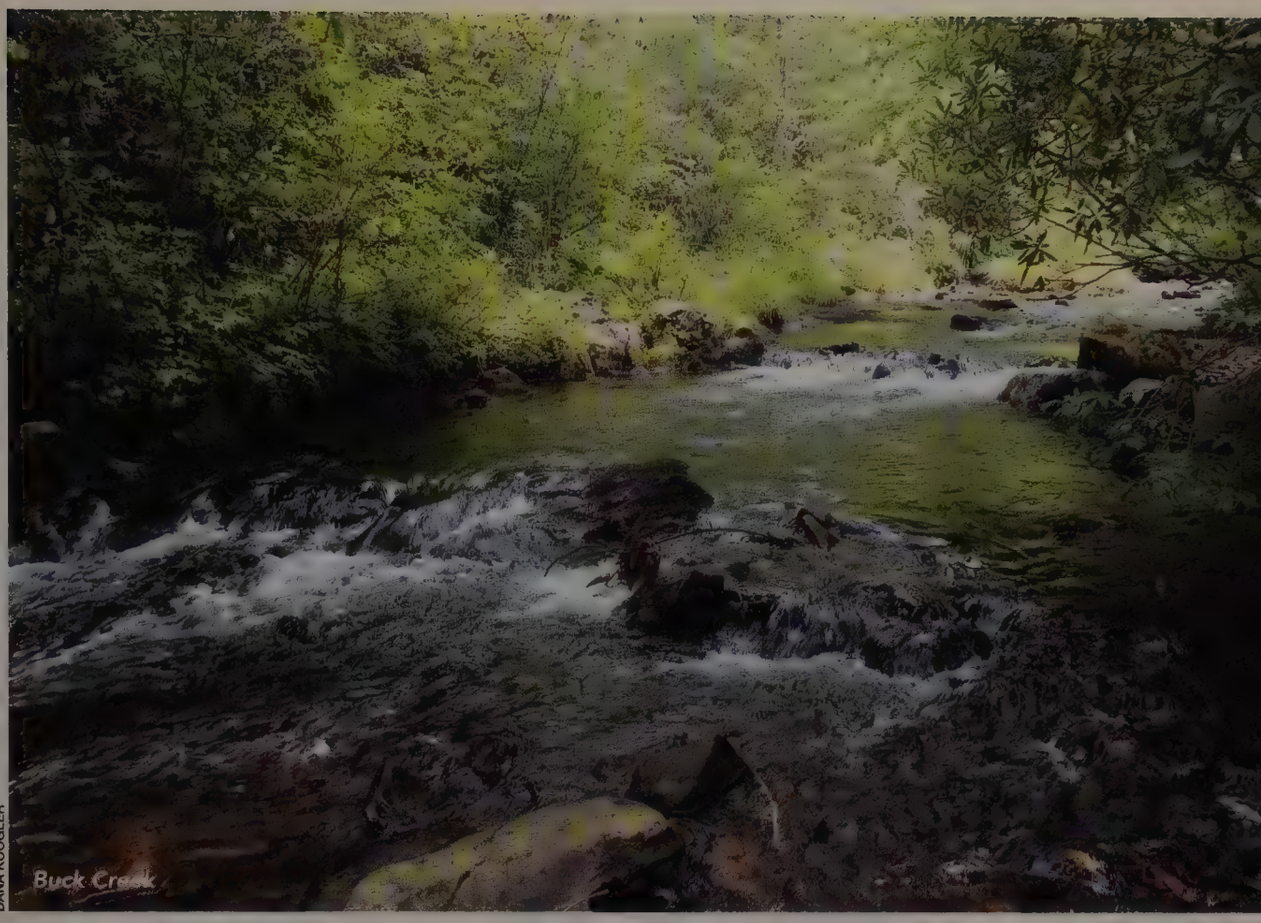
Most of the national forest is densely packed with a large variety of tree species. Some of the highest mountain tops, however, contain few or no trees. These open areas with exposed rock surfaces are referred to as balds, which are home to a somewhat different flora. Although such place names as Wayah Bald, Charley Bald, Gray Bald, and Rich Mountain Bald indicate the presence of balds in the past, some have not been burned recently and are becoming tree covered.

Because balds are increasingly rare in this forest, I was surprised, while exploring along Buck Creek east of Chunky Gal Mountain and about twenty-five miles west of Franklin, to find a sparsely forested area with an understory dominated by prairie grasses. The exposed rocks in this region of about three hundred acres consist primarily of serpentine. Serpentine

Wetland at the foot of Boteler Peak



rocks have a high content of magnesium and a low concentration of calcium. The serpentine in the Buck Creek area consists primarily of dunite and olivine. Because a high concentration of magnesium is toxic to many plants, vegetation is usually sparse and, generally, limited to rare, endemic species that have adapted.


DANA KOOGLER
Buck Creek

Before the U.S. Forest Service's land and resource management plan took effect in 1987, the serpentine areas above Buck Creek had not been managed, and so the open forest was not maintained. Beginning in 1999, however, prescribed burns were begun in an effort to kill back woody invaders, particularly white oak and pitch pine. The first burn did little to remove the trees, so in 2000, most of the trees and shrubs that remained were removed mechanically by cutting and slashing, followed by more prescribed burning. These steps made a significant difference in the vegetation. No longer were trees and shrubs making inroads into the area, and the prairie grasses that had been struggling to grow beneath them began to flourish. In addition, other plants, heretofore rare in North Carolina, started to appear and thrive. By the beginning of the twenty-first century, annual burns have prevented most woody species from encroaching. The entire barrens are not burned, only three of the four designated blocks of land. This selective burning gives the eighty kinds of butterflies and moths that live in the barrens refugia during the burning process. The area, known as the Buck Creek Serpentine Barrens, lies on west-facing and east-facing slopes from an elevation of 3,400 feet near Buck Creek to 4,000 feet on Corundum Knob.

DANA KOOGLER

Nearly ten percent of the Buck Creek Serpentine Barrens is bare rock. The remainder is dominated by prairie grasses beneath a sparse canopy of trees. The water table varies in depth and alternates from very shallow to somewhat deeper, often adjacently. After a heavy rain, water seeps across the barrens. Where the water table is shallow, wetland plants tend to occur. Where it is somewhat deeper, dry-loving plants thrive. Botanists have found that the soil depth in the barrens may be as much as thirty inches and that there is a perched water table just below the surface that provides adequate moisture for the plants growing there. Gary Kauffman, botanist for the Nantahala National Forest, has compiled a list of nearly three hundred trees, ferns, and flowering plants known from the barrens, a fairly high number of species for such a small area. The kinds of plants are even more remarkable. Beneath the sparse tree cover are grasses, many of them major components of the Great Plains prairies. These include big bluestem, little bluestem, Indian grass, switchgrass, and, perhaps most surpris-

DANA KOOGLER
Fringed gentian, *Gentianopsis crinita*

Carolina phlox, Phlox carolina

DANA KOOGLER

Since serpentine areas in the United States, particularly in California, Oregon, and Washington, often support endemic plant species, it was surprising that no endemic species had been recorded from the Buck Creek Serpentine Barrens for a long time. Recently, botanists have looked more closely at the plants in the barrens and have found two endemic species. One is Rhiannon's aster, and the other the serpentine groundsel. In addition, Ruth's little brown jug, which is found in the barrens, may be significantly distinct, including the habitat in which it grows, and therefore may be a new species. Kauffman also believes another population of groundsel may prove to be a new, distinct species.

What I found equally interesting was the intermixture of dry species and wetland species. For example, two species of louseworts almost always occur in very different habitats. I have only seen swamp lousewort as a wetland species living in fens and marshes, while I have found yellow lousewort only in dry woods. At the Buck Creek Serpentine Barrens, these two species grow close together. Similarly, two species of the orchid genus *Liparis* almost always live in very different habitats. The fen orchid is a species found in fens and other wet areas, while the common twayblade orchid lives in rather dry woods. At Buck Creek they are found in close proximity to each other. Likewise, the Appalachian violet is a dry habitat species, while marsh violet is a wetland species. Other pairs of wet and dry habitat species that caught my eye are swamp aster, a wetland species, and wavyleaf aster, a dryland species; deer-tongue grass (wetland) and broadleaf rosette grass (dryland); and swamp goldenrod (wetland) and Atlantic goldenrod (dryland). I couldn't believe that right in the middle of a large patch of prairie dropseed were specimens of American burnet and cowbane, two species I have always associated with wetlands.

VISITOR INFORMATION:
Nantahala National Forest
Tusquitee Ranger District
123 Woodland Drive
Murphy, NC 28906
1-828-837-5152
tusquiteerd@fs.fed.us

THE SOUTHERN APPALACHIAN PLANT SOCIETY

Grass of Parnassus, Parnassia grandifolia

Analysis of the flora and fauna reveals several interesting facts. About twenty of the plant species are rare in North Carolina and many of them are at the extreme edge of their overall range. In addition to flowering plants, there are very rare and endemic lower plants, such as the Appalachian liverwort, the enigmatic hornwort, and the Highlands moss. Zoologists have recorded more than eighty kinds of lepidoptera, including five that are considered rare in North Carolina.

HABITATS

Rare North Carolina Plants in the Barrens Most of the species that are rare in North Carolina are also at or near the edge of the range of their range. Northern species that are at the southern limit of their range are tufted hairgrass, drooping bluegrass, spiked muhly, Wood's sedge, fen orchid, fringed gentian, and northern shorthusk grass. Slender wheatgrass is at the southeastern edge of its range, while the southern small-leaved meadow rue is at the northern edge of its range.

Woody Plants mostly adjacent to the Barrens In addition to white oak and pitch pine, other trees in the area, some of which occasionally invade the barrens, are sassafras, Canadian hemlock, sourwood, smooth shadbush, and red maple. Among the shrubs are raisintree viburnum, southern arrowwood, maple-leaved viburnum, northern bush honeysuckle, common ninebark, maleberry, and swamp blueberry.

Ferns Kauffman has found several ferns in or near the barrens. These include marginal woodfern, southern lady fern, Christmas fern, New York fern, broad beech fern, common rockcap fern, cinnamon fern, royal fern, ebony spleenwort, eastern bracken fern, and rattlesnake fern.

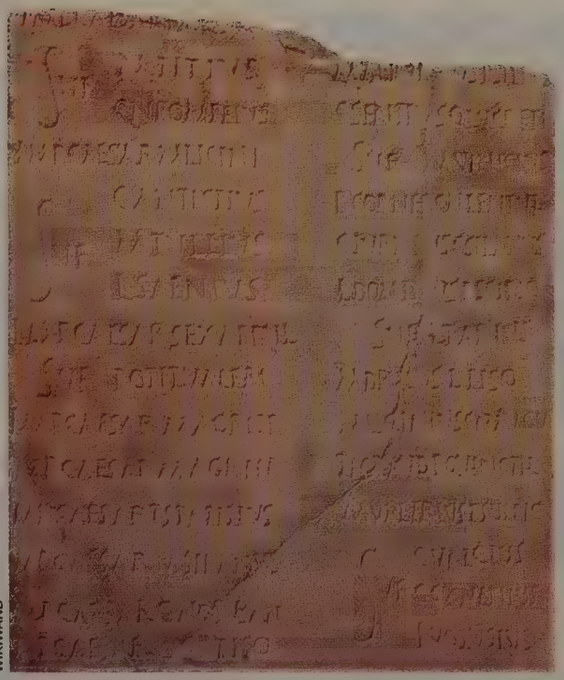
ROBERT H. MOHLENBROCK is a distinguished professor emeritus of plant biology at Southern Illinois University Carbondale.

SKYLOG BY JOE RAO

Catching Up

Leap Day, February 29th, is an artifact that dates back to 46 BCE, when Julius Caesar took the advice of the learned astronomer Sosigenes of Alexandria, who knew from Egyptian experience that the tropical year (also known as the solar year) was about 365.25 days in length. To account for that residual quarter of a day, an extra day was added to the calendar every four years. At that time, February was the last month of the year.

In order to make the transition from the Roman calendar—which had 355 days and was basically a lunar calendar—to the Julian calendar, and to get the months and various feasts and holidays back into their normal seasons, ninety extra days were inserted into the year 46 BCE. Caesar divided the ninety extra days into three temporary months. One month was added between February and March. Two other months—*Intercalaris Prior* and *Intercalaris Posterior*—were added after November. The resulting year, which had fifteen months and was 445 days long, was known as *Ultimus Annus Confusionis*, "the Last Year of Confusion."



WIKIWAND

Inscribed Roman calendar

Unfortunately, the Julian calendar was still flawed, being 0.0078 of a day—about eleven minutes and fourteen seconds—longer than the tropical year. Every 128 years, the tropical year shifted backward one day with respect to the calendar.

By 1582, the calendar had fallen out of step with the tropical year by a total of ten days. Pope Gregory XIII stepped in and, with the advice of German Jesuit mathematician and astronomer Christopher Clavius, produced our current Gregorian calendar. To catch up, ten days were omitted after Thursday, October 4, making the next day Friday, October 15. To match the length of the tropical year more closely, century years were no longer leap years, as they had been in the old Julian calendar. The exceptions to this rule are those century years that are equally divisible by 400. Thus, 2000 was a leap year, but 1700, 1800, and 1900 were not.

Calendar	Introduced	Average year	Approximate annual error introduced
Gregorian (current) calendar	1582 AD	365.2425 days	27 seconds (1 day every 3,236 years)
Julian calendar	45 BC	365.25 days	11 minutes (1 day every 128 years)
365-day calendar	Not used	365 days	6 hours (1 day every 4 years)
Lunar calendar	ancient	12–13 moon-months (variable)	Variable

Joe Rao is a broadcast meteorologist and an associate and lecturer at the Hayden Planetarium in New York City (www.haydenplanetarium.org).

FEBRUARY NIGHTS OUT

1 During the early morning hours, the Moon, just past last quarter, appears situated a couple of degrees to the upper left of the planet Mars. It rises in the east-southeast shortly before 1:00 A.M. EST and is well up in the southern sky near the meridian as dawn begins. Situated in Libra, the red planet still shows a small telescopic disk. Its north pole is tilted 14° toward Earth; the north polar cap should appear as a tiny bright speck.

3 Any time after 4:30 A.M. EST, low toward the southeast sky you'll see a broad right triangle formed by a wide crescent Moon, the planet Saturn and the ruddy first-magnitude star Antares. Saturn and the Moon are approximately eight degrees from Antares while the Moon and Saturn are separated by five degrees. Saturn is now located in the non-zodiacal constellation of Ophiuchus and rises two to three hours before the first light of dawn.

6 A very thin (six percent illuminated) waning crescent Moon forms a broad triangle with Venus and Mercury, the moon hovering about four degrees above both planets. Mercury also reaches greatest elongation on this morning, 26° west of the Sun.

7 Venus appears brilliant above the southeast horizon, rising less than two hours before sunup. Mercury rises in twilight in the south-southeast nearly one and a half hours before sunup. Look for Mercury about five degrees to Venus's lower left about 45 to 60 minutes before sunrise.

8 New Moon at 9:39 A.M. EST

13 Mercury and Venus engage in what is called a "quasi-conjunction." Neither planet passes the other in the sky but they approach each other rather closely. Venus comes within four degrees to the upper right of Mercury.

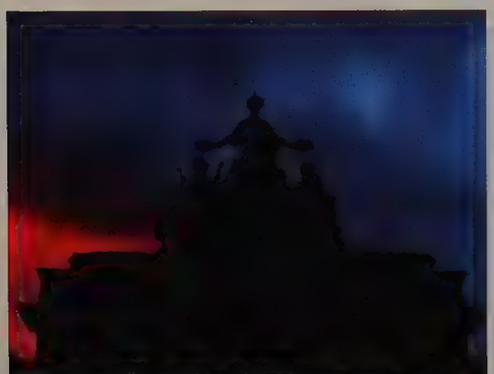
15 First Quarter Moon at 2:46 A.M. EST

22 Full Moon at 1:20 P.M. EST

23 In the eastern sky early this evening, you'll see the nearly full moon accompanied by what appears to be a brilliant silvery "star" a couple of degrees to the left—which is actually the largest planet in our solar system, Jupiter. The most prominent dark belts of Jupiter are easy to see with even a fairly small telescope. Other Jovian features can be glimpsed later in the evening with stronger optics.

29 Mars is now rising shortly after midnight, and if you look toward the southeast around 1:00 or 2:00 A.M. EST on this Leap Day morning, you'll see it about six or seven degrees below and slightly to the left of the waning gibbous Moon. Fiery-hued Mars now rivals Procyon, the eighth brightest star in the sky, and continues to brighten as it gets closer; it's now 101 million miles from Earth.

There is no Last Quarter Moon in February. January and March both have two Last Quarter Moons.



This Gulf of Fire: *The Destruction of Lisbon, or Apocalypse in the Age of Science and Reason* by Mark Molesky, Alfred A. Knopf, 2015; 512 pages, $35.00

Few events in history have had more physical or social impact than the triple disaster that befell the city of Lisbon on November 1, 1755. At about 9:45 A.M., while churches were packed with parishioners celebrating All Saints Day, an earthquake approaching a magnitude of 9.0 leveled the city, burying entire congregations under the rubble of collapsed roofs and filling the narrow streets with debris.

In the neighboring Atlantic Ocean, several hundred miles offshore to the west, the sudden crustal uplift spawned a devastating tsunami. It reached the mainland about thirty minutes after the first tremors, entered the narrow mouth of the Tagus River, and bulldozed into Lisbon's harbor several miles upstream. Throngs of dazed and agitated quake survivors who had made their way to the waterside were immediately swept away, while massive ships were jammed inshore amidst the jumbled ruins.

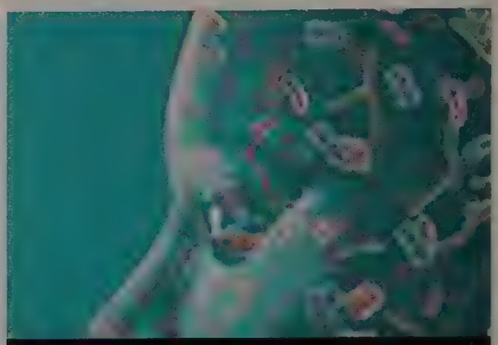
Fires immediately broke out at "a hundred places throughout the city," set off by votary candles, fireplaces, and ovens, and fueled by the structural timber and opulent household furnishings of what was, at the time, one of the richest cities in Europe. Dozens of small blazes soon coalesced to create a firestorm, an inferno on the scale of the Great Fire of London in 1666. The main fire burned for a week, indiscriminately cremating both the dead and the living trapped beneath fallen buildings, and reducing much of what remained of the city to ashes. Flames continued to appear in the basements of ruined houses and shops for over a month.

Seton Hall associate professor of history Mark Molesky draws on an enormous quantity of first-person letters, memoirs, and contemporary documents to create the literary equivalent of a virtual reality simulation of the cataclysm. Modern scientific interpretations of the events appear, but the great virtue of Molesky's narrative lies in its evocative re-creation of the experiences of survivors and of the zeitgeist of mid-eighteenth century Europe.

To the devout, the destruction of their city was a sign of God's retribution for sinful excess, a latter-day replay of the incineration of Sodom and Gomorrah. Many believed that they were witnessing not only the end of a city, but the beginning of the Apocalypse, foretold in Revelation. "It is impossible in Nature to behold a Picture that bears a stronger Resemblance to the last great solemn Day," a Portuguese official commented, likening Lisbon to "one of the wide Gates of the vast Empire of Death."

To those inspired by Enlightenment values, however, the quake was a natural event, an opportunity to test geological theory against data provided by eyewitness accounts. We need not look to an angry God for an explanation of the disaster, wrote Immanuel Kant, "we have the causes under our feet." Voltaire included the Lisbon earthquake as one of the travails of the naïf Candide, sardonically implying that there was no divine beneficence underlying raw nature.

Few of their contemporaries fully embraced Kant's naturalism and Voltaire's cynicism—superstition and faith persist even into the twenty-first century—but the times were changing. Death and destruction in Lisbon gave life to modernist scientific sentiment in the years that followed, marking the event, Molesky writes, as "a true crossroads in the history of the West."



Welcome to the Microbiome: *Getting to Know the Trillions of Bacteria and Other Microbes In, On, and Around You* by Rob DeSalle and Susan L. Perkins, Yale University Press, 2015; 264 pages, $32.50

Modern microbiology gives new meaning to the ancient Greek maxim "Know Thyself." We are not entirely, or even mostly, human, at least at the cellular level, according to Rob DeSalle and Susan Perkins, curators at the American Museum of Natural History. Rather, "you should imagine...your body as a collection of multiple dynamic ecosystems made of very tiny, and very biologically diverse organisms." Your skin, your mouth, your lungs, your digestive tract—all host communities of commingled microbes, more than 10,000 different species according to current estimates. In other words, you are not who you think you are: up to 90 percent of the cells in your body, comprising three percent of your body mass, are microbial, not human.

Ever since Pasteur, we've known that there are microbes in and around us. But it's only in the last few decades that we've realized just how many. Before the advent of biomolecular chemistry, the principal way of identifying microbes was to grow them on agar culture in a Petri dish. To conduct a census

of the bacterial content of pond water or of human saliva, you would place a sample on a culture plate and wait to see expanding colonies of discoloration on its surface. Several thousand species of bacteria could be identified this way, but when DNA analysis emerged three decades ago, it was recognized that many of the more interesting organisms do not multiply on culture plates.

In 1985, microbiologist Norman Pace reasoned that the logical way to identify microbes was to analyze the entire mix of DNA sequences in a sample. The result was stunning—it's estimated that there are at least tens of millions of different bacterial species, most of which had been missed in the past because they are difficult, if not impossible, to culture. Most microbes are communitarian creatures; they require not just a source of nourishment, but an entire ecosystem to flourish. Without the proper size and mix of diverse species and the right brew of environmental chemicals at the ideal temperature and acidity, an isolated species will wither and die.

Since Pace's pioneering work, DNA sampling techniques have advanced to the point that researchers can quickly and routinely characterize rich mixes of microbial material and match their sequences against growing libraries of millions of known genomes. Because of the importance of microecology to human health, the National Institutes of Health has been funding an initiative called the Human Microbiome Project (HMP), employing state-of-the-art DNA sequencing to characterize the diversity of microbes in, on, and around our bodies, and the role they play in maintaining health and causing disease.

DeSalle and Perkins report on some of the many unexpected results of this research. Microecology is clearly a field that is coming of age, revealing a biosphere that is far more complex than we ever imagined. Both you and your microbiome will surely find this report on microecology's latest findings entertaining, informative, and filled with food for thought.

Meathooked: *The History and Science of Our 2.5-Million-Year Obsession with Meat* by Marta Zaraska, Basic Books, 2016; 272 pages, $26.99

Current concerns over the burning of fossil fuels, highlighted by the Paris UN climate conference in December, overshadow other ways in which Earth's resources are being stretched to the limit. Consider our appetite for red meat and poultry: the average Westerner ate 22 pounds per year in the early 1800's; by 2013, that number had risen to 95 pounds (United States consumers ate a whopping 275 pounds in 2013). Journalist Marta Zaraska reports that this trend simply cannot be maintained.

Grain and water requirements of livestock production already place critical demands on agricultural resources. As developing nations catch up with the West, worldwide demand for meat, if it follows historical patterns, will quickly exceed sustainable levels. To make matters worse, livestock generate greenhouse gases beyond those produced by fossil fuels, contributing about as much to the global warming budget as the emissions from all cars, trucks, ships, and airplanes combined.

Clearly, the dinner table of the future must feature less meat—but is that a bad thing? The downside of industrialized agriculture has been well documented in such books as Michael Pollan's *The Omnivore's Dilemma*. Zaraska focuses on why we crave meat in the first place and whether a meat-free world is a utopian fantasy or a realistic adaptation. Meat tastes good, she concedes, noting that "our bodies are designed to prioritize protein and actively seek it out," but that can't explain why a vegetarian diet won't suffice. She cites numerous scientific studies showing that balanced plant-based diets easily satisfy protein requirements, not to mention provide many other nutritional benefits.

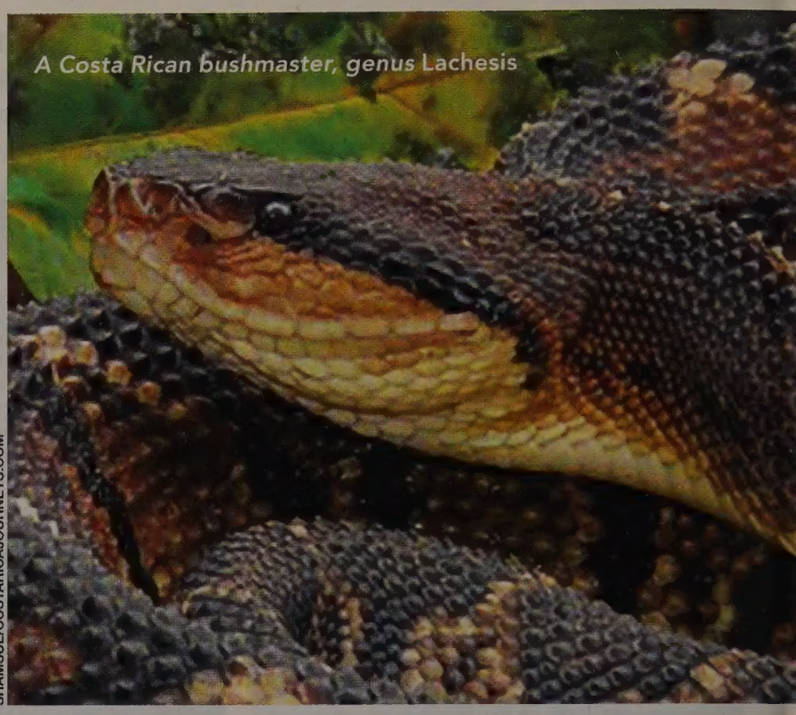
Meat has appeals beyond taste, which make it easier for advertisers to succeed and harder for carnivores to shake the habit. Perhaps because it is historically more expensive, meat has long been associated with luxury: a steak on the plate has the same cachet as a Rolex on the wrist. Meat is also associated with times of plenty, with feasting, and even with virility and sexual potency. "To stop eating flesh," Zaraska quips, "means risking becoming veggie-like, as fast as a cabbage and as mighty as a head of lettuce."

Yet, as a matter of sheer environmental necessity, Zaraska advocates a more veggie-centered diet. Less pollution, fewer reasons to worry about antibiotic resistance, reduced food poisoning, better use of water and arable land—all will follow as meat fades from our diet. "It's time to switch from meat toward a diet based on vegetables, grains, fruits, and legumes," she concludes, but cautions that "this change won't happen overnight. The meat hooks are far too strong for that." As I closed her smartly reasoned book, nodding agreement, I couldn't help but think of...bacon.

Laurence A. Marschall is a professor of physics at Gettysburg College in Pennsylvania. His most recent books, coauthored with Stephen P. Maran, are Pluto Confidential: An Insider Account of the Ongoing Battles over the Status of Pluto *and* Galileo's New Universe: The Revolution in Our Understanding of the Cosmos *(both BenBella Books, 2009).*

Bushwhacked

SEAN O'DONNELL



A Costa Rican bushmaster, genus Lachesis

SHAMSUL/COSTARICAJOURNEYS.COM

The "white fang club" is made up of a cadre of field biologists who have been bitten by venomous snakes in the line of duty. My membership-qualifying experience may be a valuable lesson on how *not* to respond if bitten.

While teaching a tropical field course in a lowland rainforest in Costa Rica, I was following an army ant foraging column with a small group of students. When the ants entered a tangled tree-fall gap, I went around the mass of vegetation to try to pick up the ant column on the other side. Ironically, I avoided entering the gap with the students in part because of concern about snake encounters. On the far side, I noted a flock of birds attending the ant raid. As I raised my binoculars, I felt a sharp and tremendous pain in my left foot. I yelled out and removed my boot, thinking that a bullet ant or scorpion had fallen in and stung me. I removed my sock and saw a single bloody puncture wound on my heel. But there was no other evidence; I have no recollection of seeing a snake immediately before or after I felt the sudden pain.

Soon afterwards, I lost my vision and became dizzy, disoriented, and panicked. After sitting for a few minutes, however, I was able to get up and, with some support, walk slowly back to the lab clearing. When I developed a pounding headache, I raised the possibility to the gathering crowd that I had been bitten by a snake and hit by only one fang. I was assured by two fellow faculty members (including a herpetologist) that my wound and subjective experience were consistent with a bullet ant sting and not with a snake bite. We looked over my boot, and found no obvious punctures or venom.

I walked back to the dining hall, ate lunch, rested for two hours, attended a lecture, and consulted with students. After dinner, I participated in a night hike searching for amphibians and—again ironically—snakes in a nearby swamp. I had a great deal of pain in my foot and lower leg and a bad headache, but I was not otherwise compromised. Around 10:00 P.M., I noted a bruised swelling (hematoma) forming near the bite wound. When I used the bathroom, there was a small but noticeable amount of blood in my urine. Upon my insistence, I was taken to the local medical clinic. Unfortunately, and surprisingly, the doctor who examined the puncture wound and hematoma also concluded it was not a snake bite. The doctor attributed the blood in my urine to a very rare but dangerous immune reaction that could occur in response to "any kind of venom," and he recommended that I seek care in Costa Rica's capital city, San José.

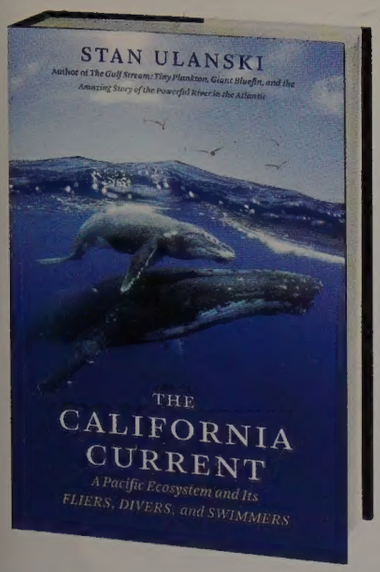
After a two-hour drive and a battery of tests, results came back, showing my blood cell counts and other vital signs were "off the charts." I had been bitten by a viper. Luckily, Costa Rica produces a polyvalent antivenin that is effective against all local vipers. The hospital promptly dosed me with ten vials. Once I had recovered, I spoke with the attending physician, who confirmed that my situation had been very serious and I was lucky to have survived.

There are two important lessons to take from this experience. First, snake bites are not unitary in their presentation. Even people with extensive tropical field experience, and those who have seen viper bite cases, may not be in a good position to recognize a wound as a snake bite.

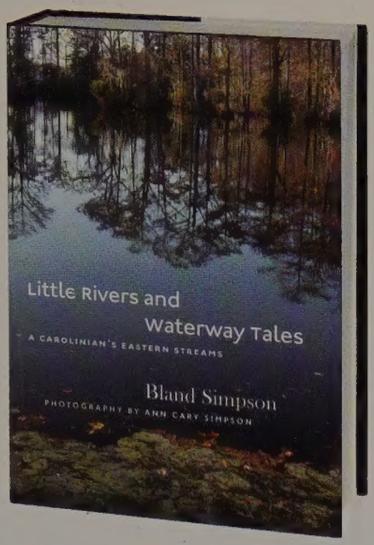
Second, if there is even a remote possibility that a person was bitten by a viper, bring the victim immediately to a fully-staffed hospital. Time is truly of the essence. Internal physiological distress is not always clearly manifested in the victim's demeanor or subjective state. Given my early suspicions that I had been bitten by a snake, I should have insisted upon treatment right away.

Upon returning home, I re-examined my boot under a strong lamp and found the two punctures apparently made by the snake's fangs, only one of which penetrated the sole. The punctures were twenty-seven millimeters apart, leading a Costa Rican herpetologist to estimate that the snake was over seven feet long and most likely a bushmaster. Even with treatment, human mortality rates to this species' venom exceed fifty percent. Before returning to field work, I purchased a very good pair of snake-proof boots.

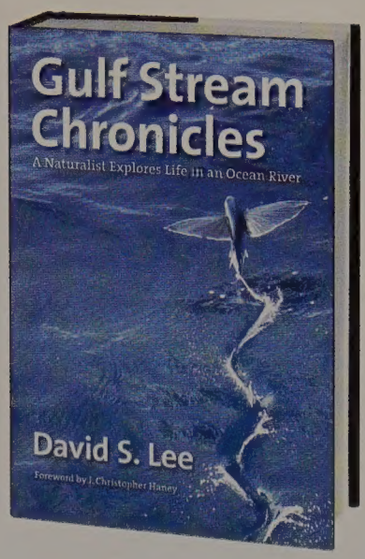
SEAN O'DONNELL is professor of Biodiversity, Earth and Environmental Science at Drexel University. His past articles in Natural History *include "Exploiting the Infantry" [7-8/14] and "Hug with Caution" [4/15].*



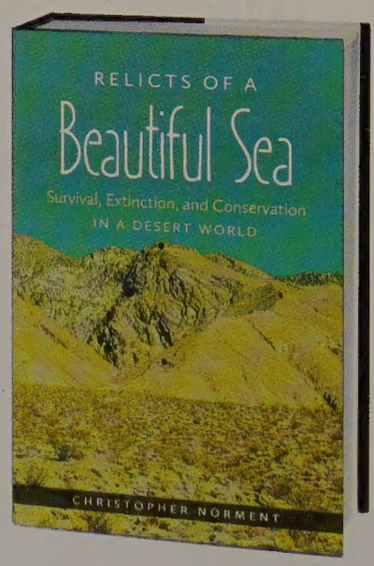
"I enjoyed reading this book, and I especially liked the historical context. There were a lot of things that I wasn't aware of that now make more sense!"
—**Daniel P. Costa,** Institute of Marine Sciences, University of California, Santa Cruz



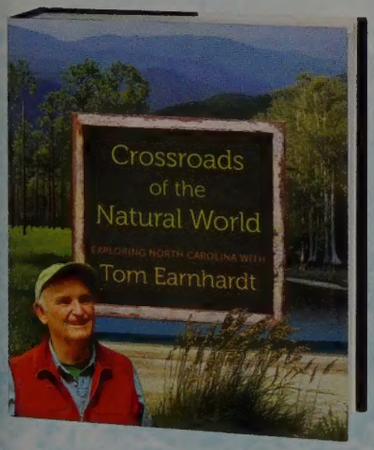
"The authors are kin to the salt air and the rising tides. They chronicle passions for other places, other times, and other people, for history, and for natural history. This book presents a striking vision of North Carolina written by the folks who know it best."
—**John Lane,** Wofford College



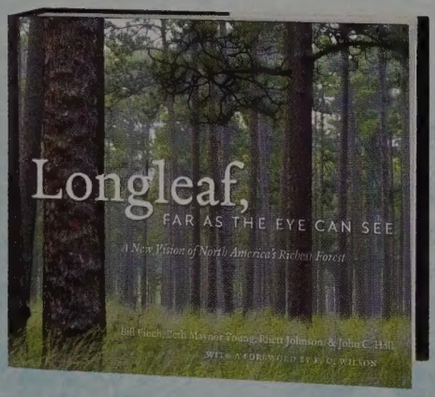
"The public would do well to become aware of the many biological treasures that lie within the waters of the Gulf Stream. There is no better place to start that education than with David Lee's highly entertaining natural history of the current and the many species that depend on it."
—**Chuck Hunter,** U.S. Fish and Wildlife Service



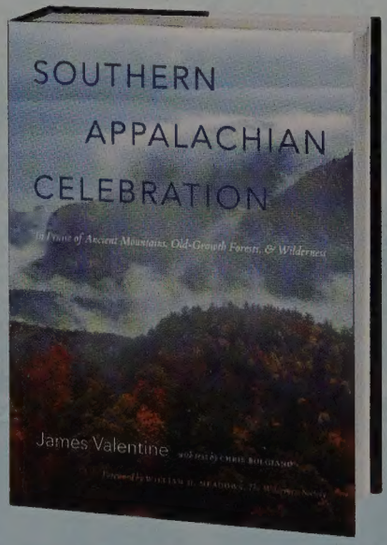
"The marvel of aquatic animal life in isolated, seemingly hostile desert surroundings of the Death Valley region is beautifully captured in this blend of natural history, the hard realities and occasional successes of conservation biology in the region, and personal reflections on nature and human foibles."
—***Copeia***



"Tom Earnhardt worries, rightly, that we live in a world of too much information and too little inspiration. Step out into the natural world of North Carolina with this most congenial mentor and you'll receive just the right dose of each. And some wisdom and humor to boot."
—**Chris Canfield,** Vice President, National Audubon Society

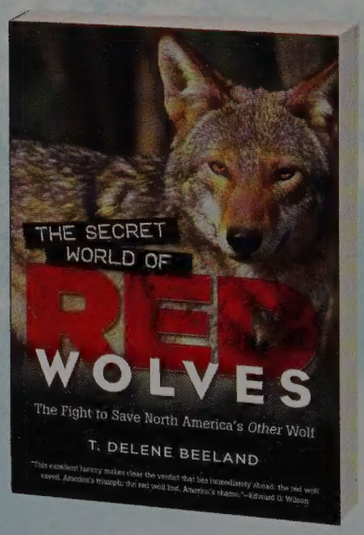


"I lost several hours paging through the evocative pictures in this book, and the text is equally absorbing."
—***The New York Times***



"Valentine has captured the many wonders of this region in large-format photos of great color, detail, and beauty."
—***The Bloomsbury Review***

—NOW IN PAPERBACK—



"Fascinating, a must-read for both scientific and popular audiences."
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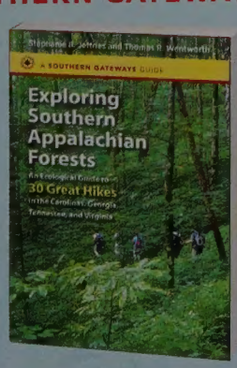

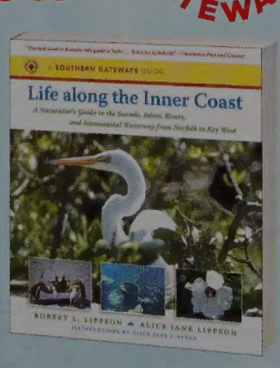

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